

Fig. 1A

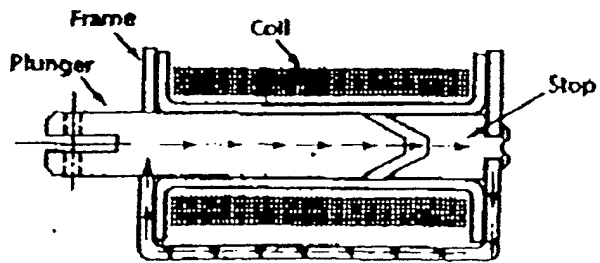


Fig. 1B

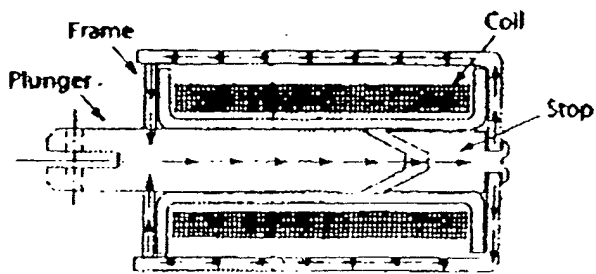
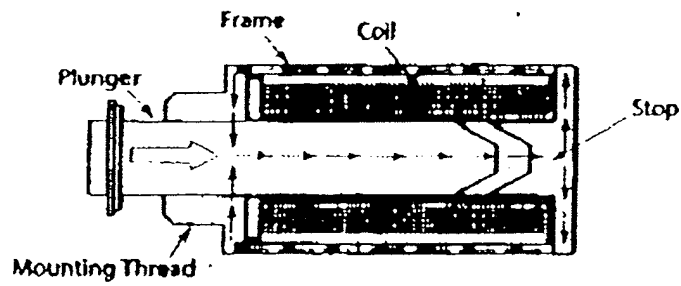


Fig. 1C



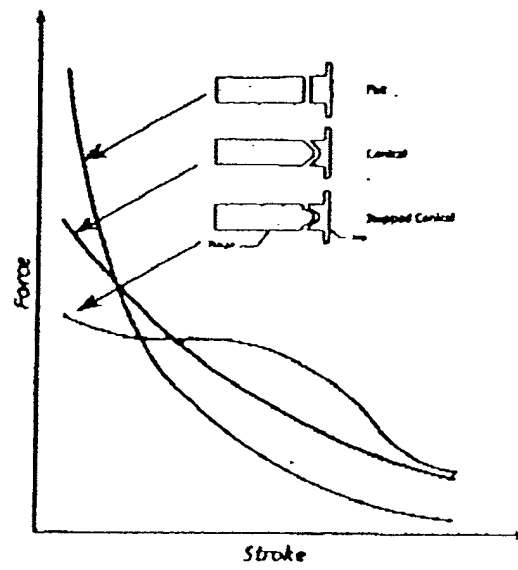


Figure 2

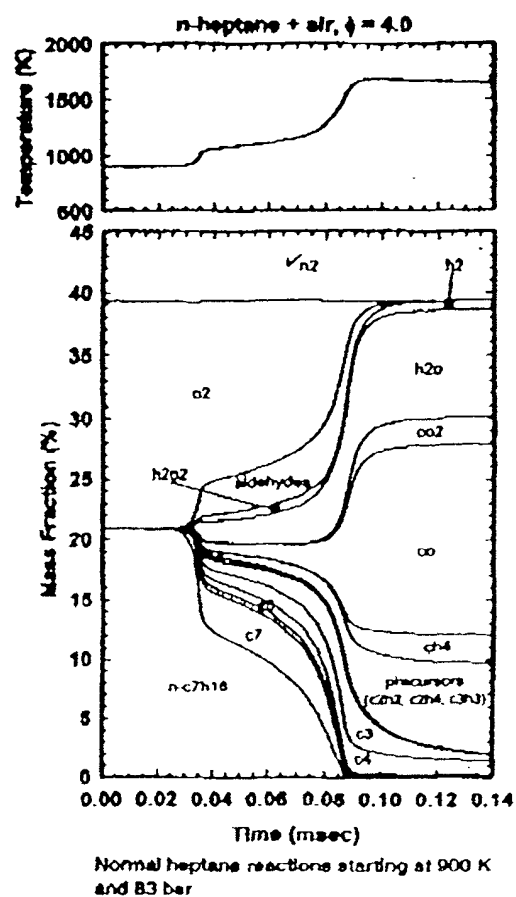
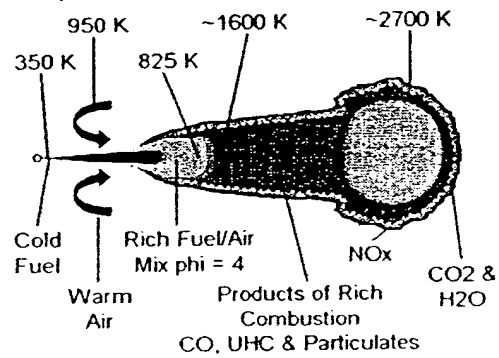


Figure 3

Temperatures



Chemistry

Summary of fuel burning processes

Figure 5

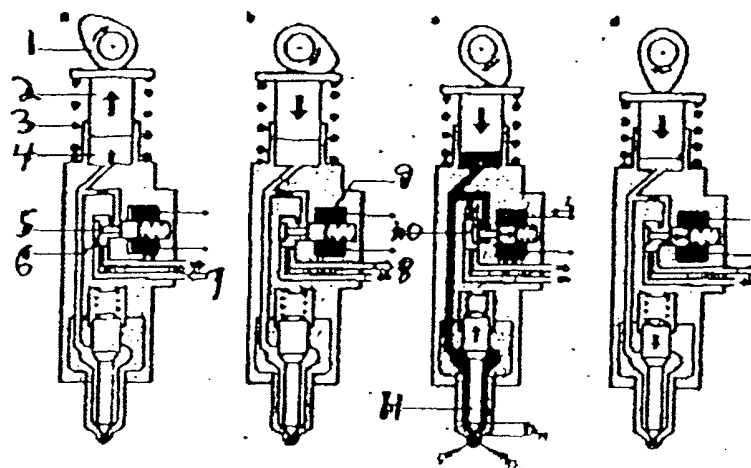


Fig. 6A

Fig. 6B

Fig. 6C

Fig. 6D

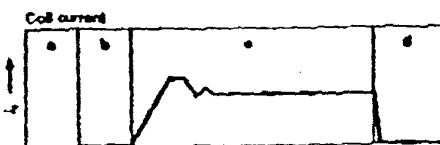


Fig. 7A

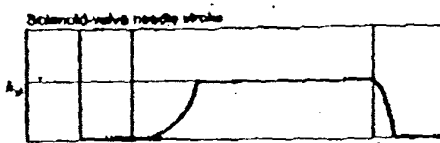


Fig. 7B

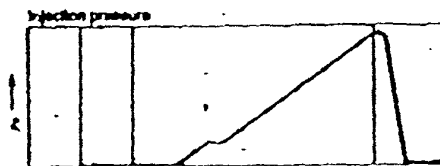


Fig. 7C

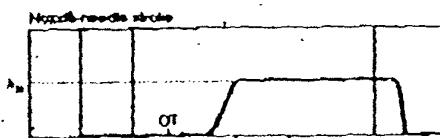


Fig. 7D

Timing in crank angle →

Wave Form Diagram: Operation of Fuel Injection Nozzle

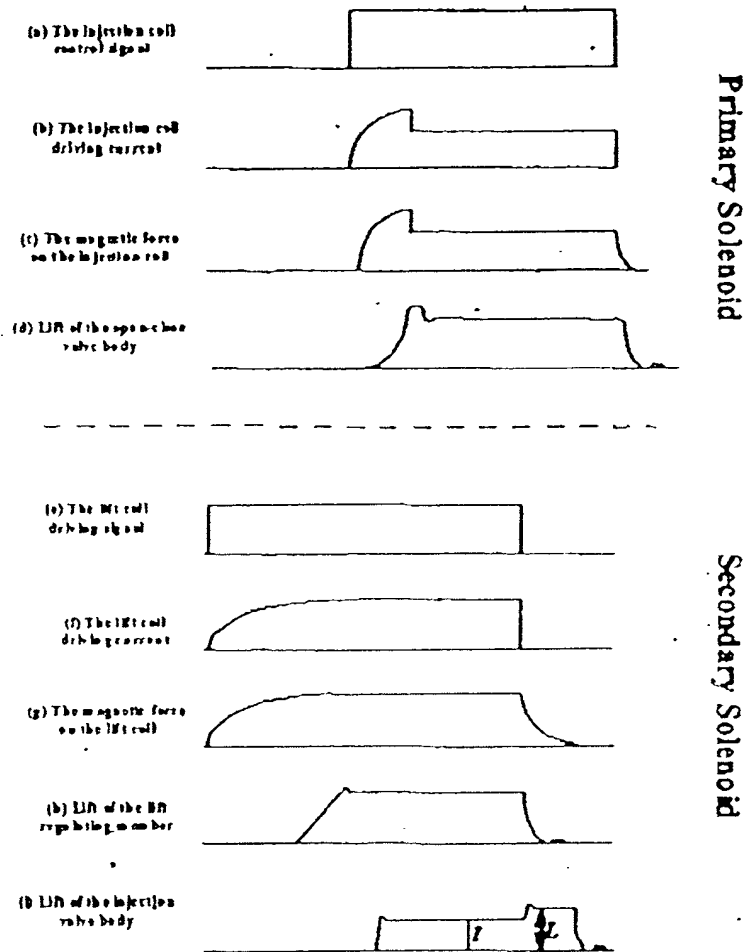


Figure 8

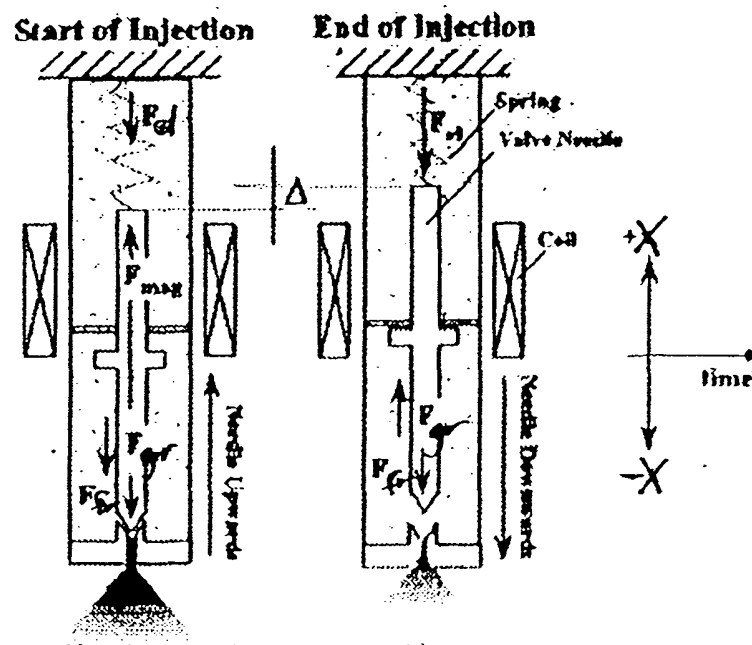


Figure 9

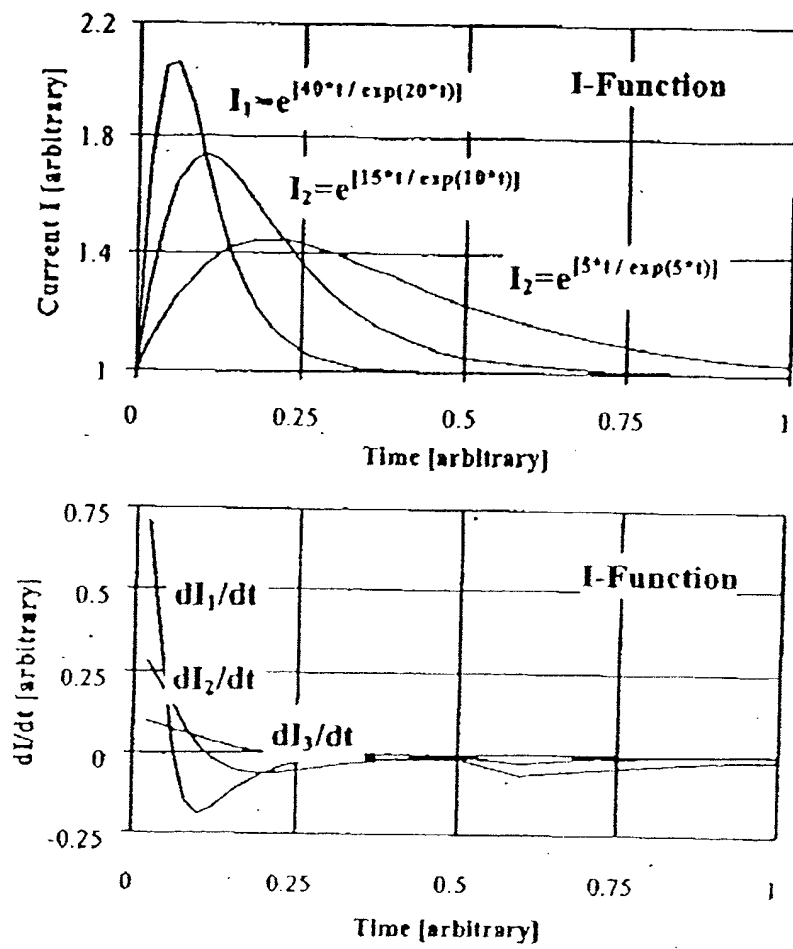


Figure 10

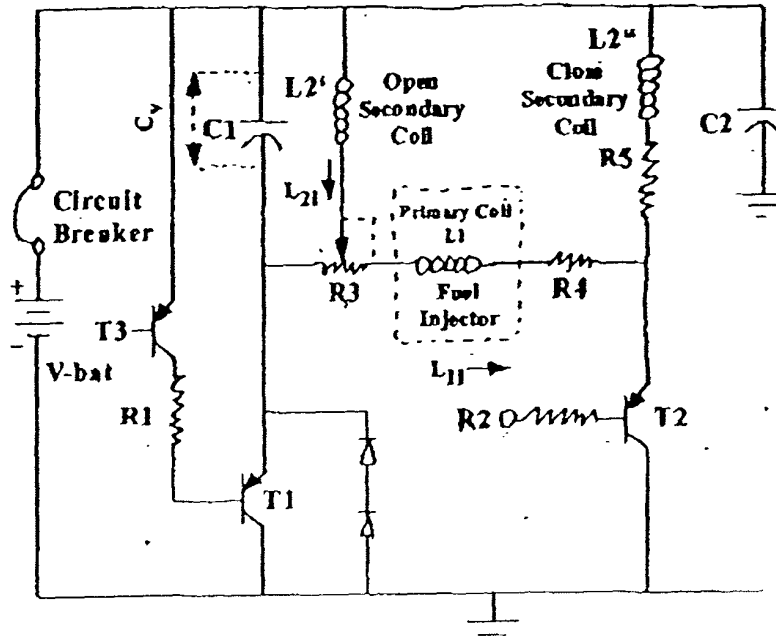


Fig. 11A

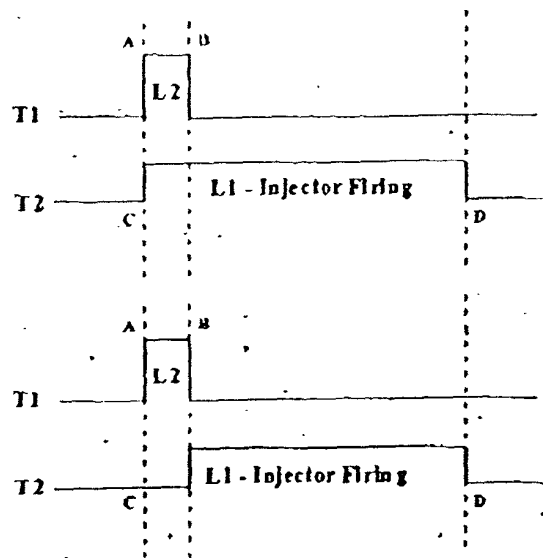


Fig. 11B

Simultaneously Charged Secondary Coll: $f = 40$ Hz
 A=T, B=C, C=A+charge, D=C+inj. duration

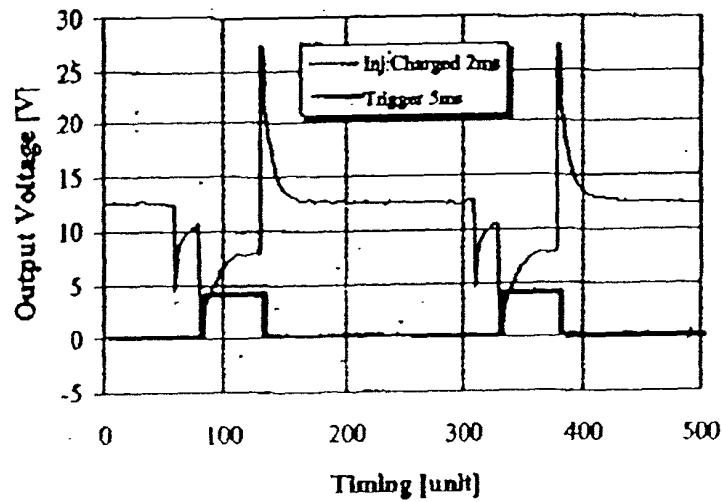


Fig. 12A

Precharged Secondary Coll: $f = 40$ Hz:
 A=T, B=A+charge time; C=A, D=C+inj. duration

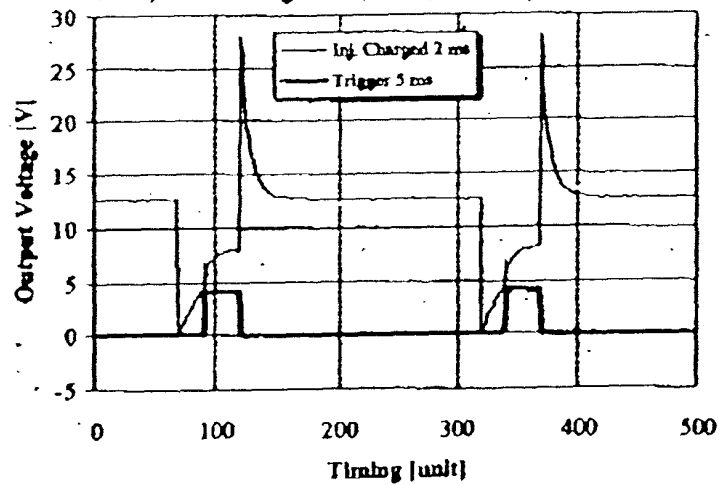


Fig. 12B

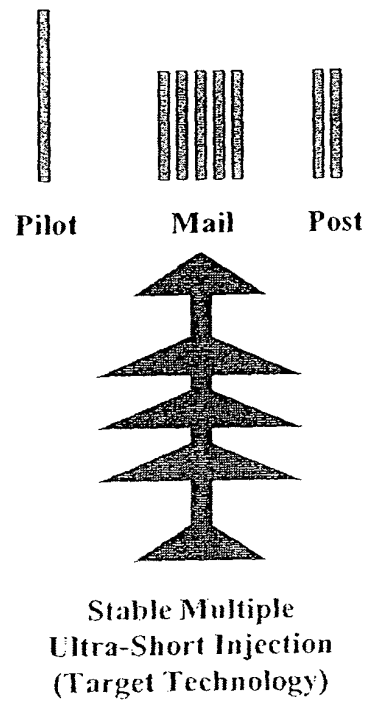


Figure 13

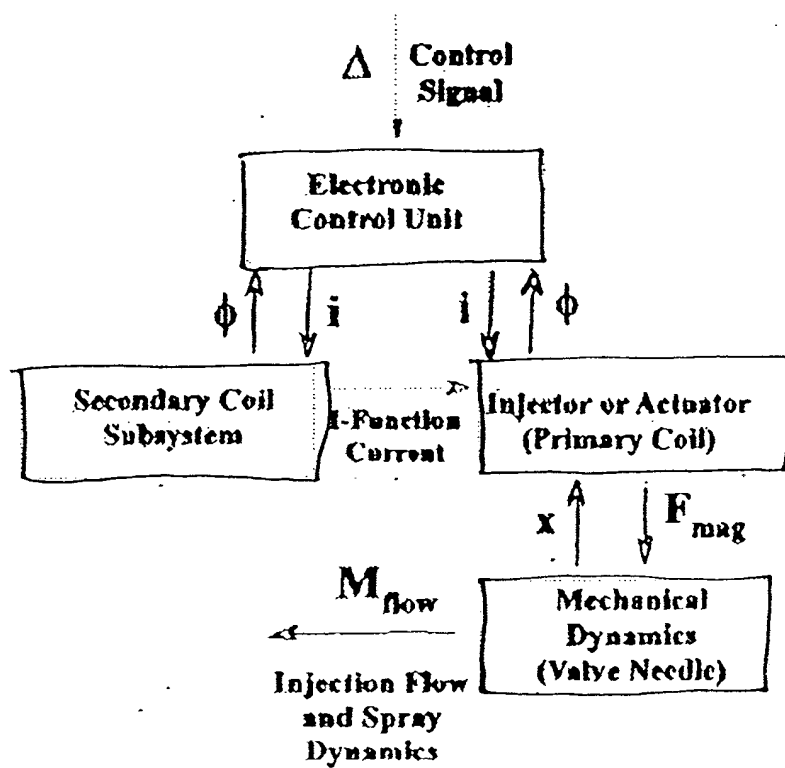


Figure 14

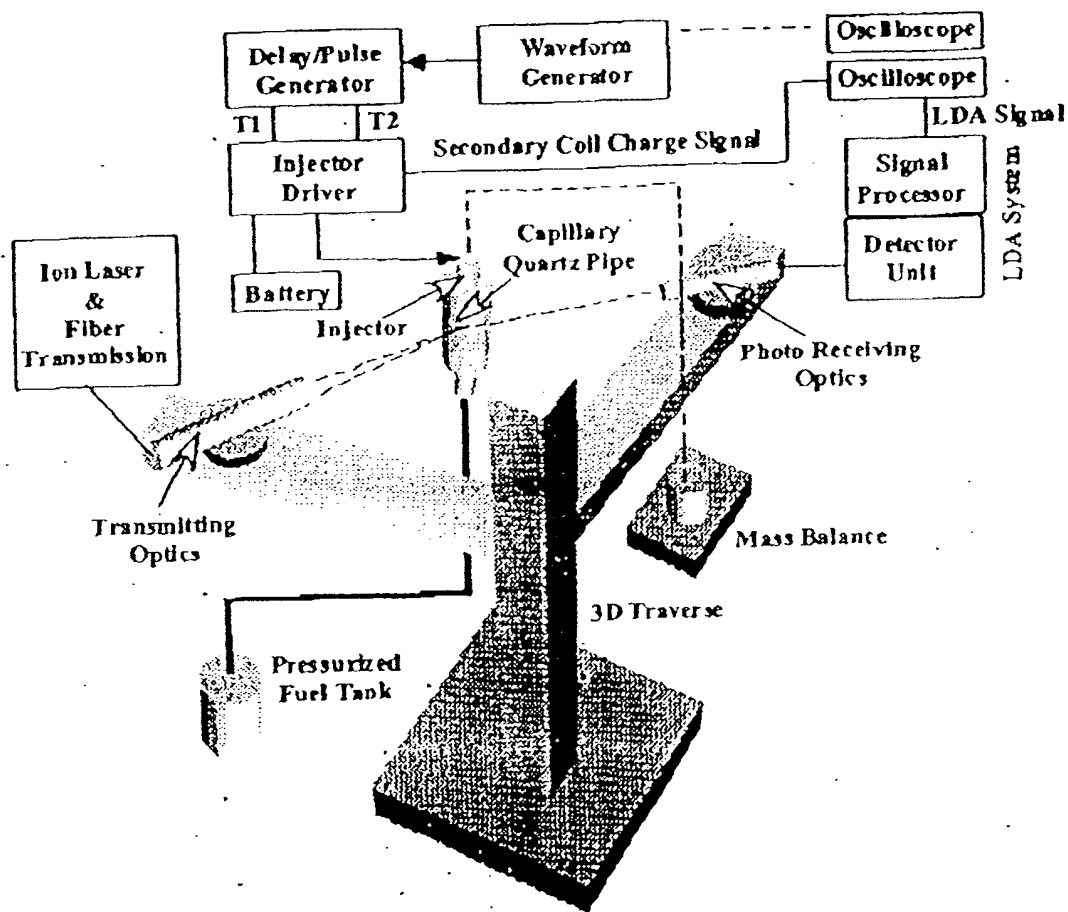


Figure 15

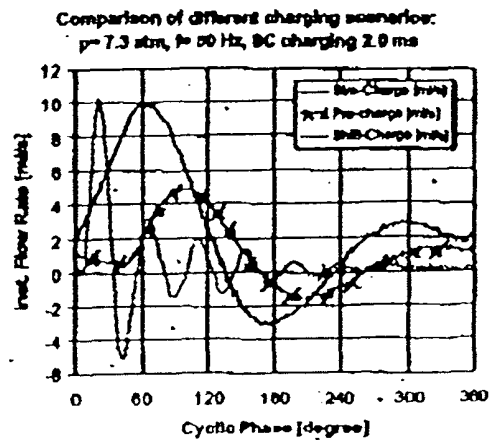


Fig. 16A

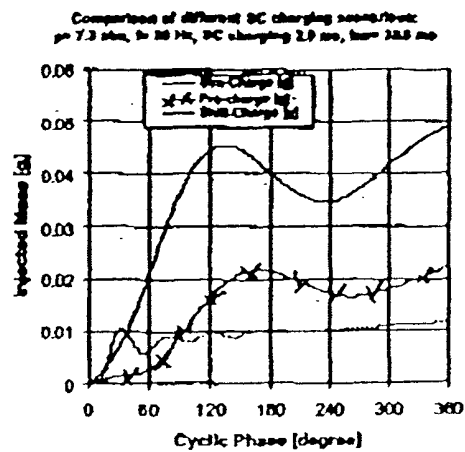
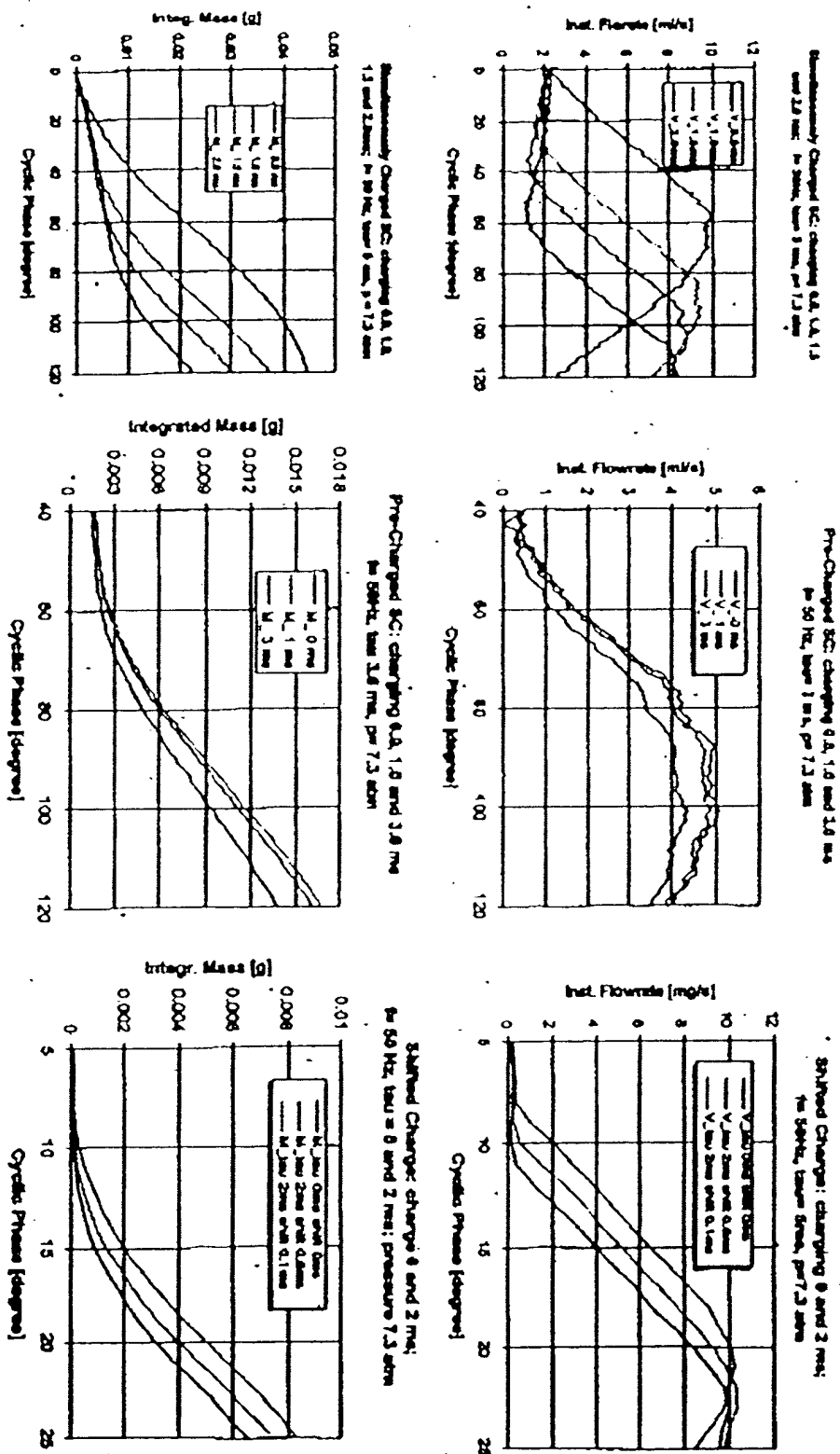


Fig. 16B

Figure 17



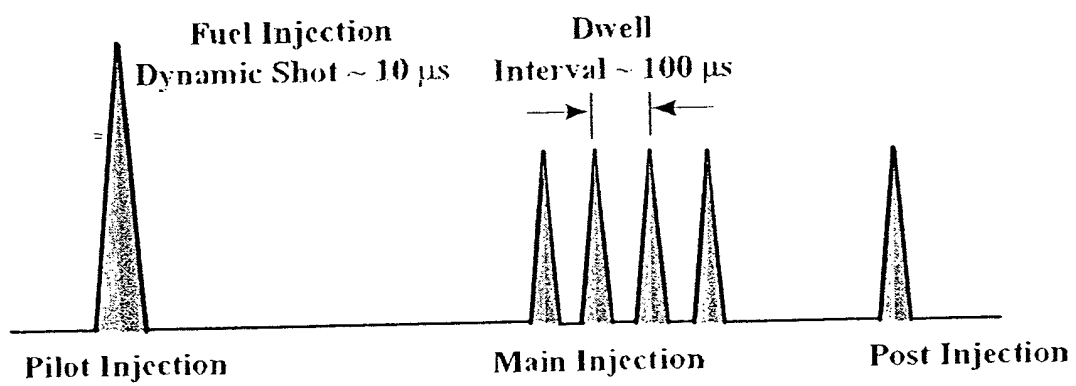


Figure 18

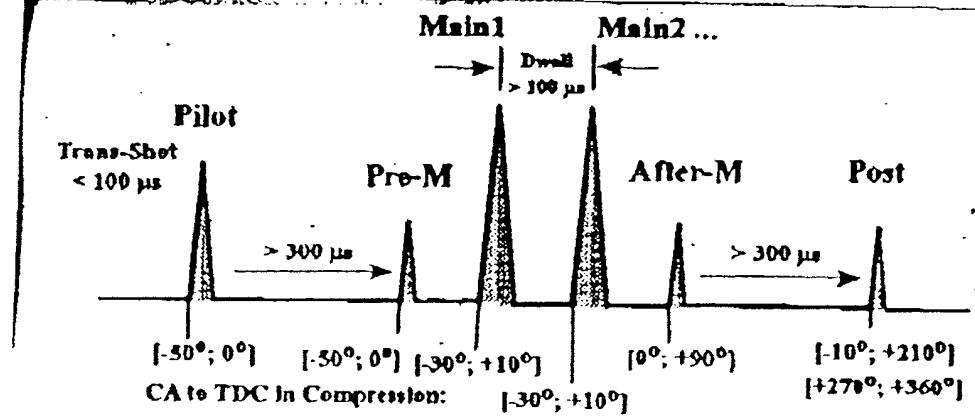


Figure 19

#	Injector	L_mean μH min	L_mean μH max	R_mean Ω min	R_mean Ω max	Time L/R μsec averaged	ω21 Freq R/L kHz averaged	0.5*I ² *L/T E_peak W L_p 18A	E_hold W L_h 12A	4*E_peak W	ω22=ω21/2 R/L_22 kHz	T22=T21/2 T2=1/R_22 μsec	L_22 μH Lp 18A R=L/T	R_22 Ω R=L/T
1	Bosch Engine I	65.73	65.75	0.45	0.45	146	6.85	72.9	4.7	291.6	3.42	292	526	180
2	II	76.24	76.35	0.35	0.45	191	5.24	64.8	5.5	259.2	2.62	381	610	160
3	III	68.48	68.41	0.35	0.45	171	5.84	64.8	4.9	259.2	2.92	342	548	160
3	IV	69.42	69.58	0.35	0.45	174	5.76	64.8	5.0	259.2	2.88	348	556	160
4	addit: V	79.79	79.85	0.35	0.45	200	5.01	64.8	5.7	259.2	2.51	399	639	160
5	VI	84.75	84.84	0.35	0.45	212	4.72	64.8	6.1	259.2	2.36	454	678	160
6	VII	79.69	79.69	0.35	0.45	199	5.02	64.8	5.7	259.2	2.51	398	638	160

Figure 20

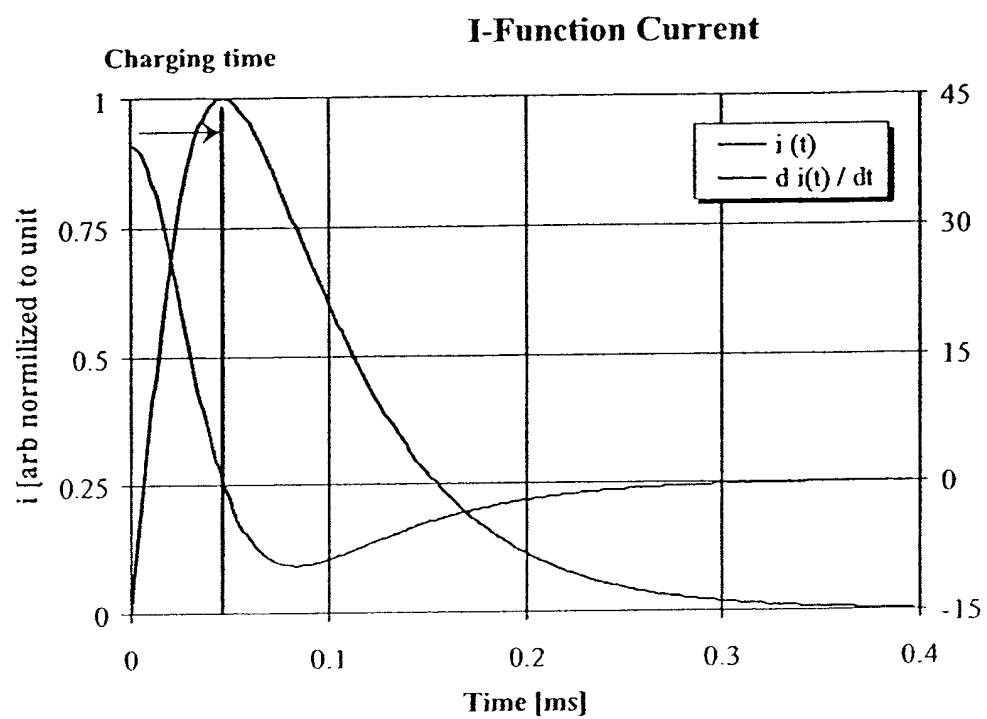


Figure 21

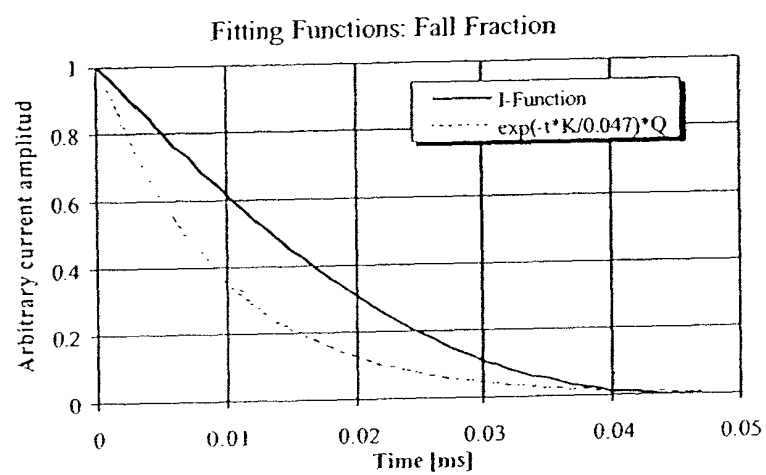
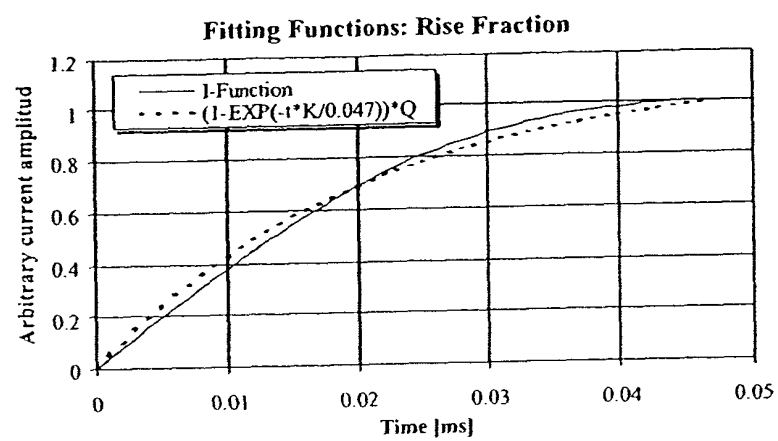


Figure 22

No.	Parameter	Calcul formula	Dimension	Value	Control	Device/Unit
1	Inductance	L, measured	μH	#REF!	L/R Meter IIB	Bosch injector I
2	Resistance	R, measured	Ω	#REF!	Mutimeter	Bosch injector I
3	T-Response	L/R	μs	#REF!	HP infinum scope 500 MHz, 1GSa/s	Bosch profile
4	F-Response	R/L	kHz	#REF!	HP infinum scope 500 MHz, 1GSa/s	Bosch profile
5	Cycle [Hz] 33.33	considered	degree ms pts	360 30.0 16000	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM
6	P Injection offset "-X deg BTDC"	considered START	degree ms pts	157.5 13.13 7000	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM
7	M Injection offset "TDC"	considered	degree ms pts	180 15.00 8000	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM
8	P_M interval	P_off - M_off X BTC	degree μs pts	22.5 1875 1000	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM
9	Normal injection "-X deg BTDC"	max 2.2 ms	degree μs pts	26.4 2200 1173	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM
10	P_duration= M_duration	considered	degree μs pts	7.2 600 320	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM
11	P_M_dwell	(P_off - M_off)-P_dur	degree μs pts	15 1275 680	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM
12	Total Injection Duration	P_dur +dwell+M_d_off	degree μs pts	30 2475 1320	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM

Figure 23

Scales		I [A]	2.0	t [ms]	0.200	T [pts]	16000					
		L [mm]	9.8	L [mm]	14.1	V_arb [-]	1					
		v/L [A/mm]	0.204	v/L [ms/mm]	0.01418	R [Ohm]	0.45					
						T [ms]	30.0					
first shot [us]		600	points	320	total pts			320	number of sine cycle		5	
second shot [us]		600	points	320	exp_rise			9.36				
dwell interval [us]		1275	points	680	exp_fall			9.60				
Profile	Phase	τ_{lin} [mm]	L_lin [mm]	τ_{abs} [ms]	L_abs [A]	τ_{pts} [-]	L_arb [-]	V_abs [V]	$\Delta \tau_{pts}$ [-]	ΔL_{arb} [-]	ΔV_{abs} [V]	
MI_33_2x600_1275_SC												
τ_{off} [pts]	7000											
	157.5°	A	0.0	0.0	0.000	0.00	7000	0.000	0.000	0	0.000	
		B	I-Function	First Peak	0.175	17.80	7093	1.000	8.010	93	1.000	8.010
		C	3.6	56.2	0.051	11.46	7121	0.644	5.159	27	-0.356	-2.851
		D	calculation	56.0	0.280	11.42	7270	0.642	5.141	149	-0.002	-0.018
		E	I-Function	total	0.094	0.00	7320	0.000	0.000	50	-0.642	-5.141
CD_osc	4.5	2.8	0.600	0.57	61	0.032	total	320				
			0.128	0.57			0.257					
τ_{off} [pts]	8000											
	180°	A	0.0	0.0	0.000	0.00	8000	0.000	0.000	0	0.000	0.000
		B	I-Function	First Peak	0.175	17.80	8093	1.000	8.010	93	1.000	8.010
		C	3.6	56.2	0.051	11.46	8121	0.644	5.159	27	-0.356	-2.851
		D	calculation	56.0	0.280	11.42	8270	0.642	5.141	149	-0.002	-0.018
		E	I-Function	total	0.094	0.00	8320	0.000	0.000	50	-0.642	-5.141
CD_osc	4.5	2.8	0.128	0.57	61	0.032	total	320				
							0.257					

Figure 24

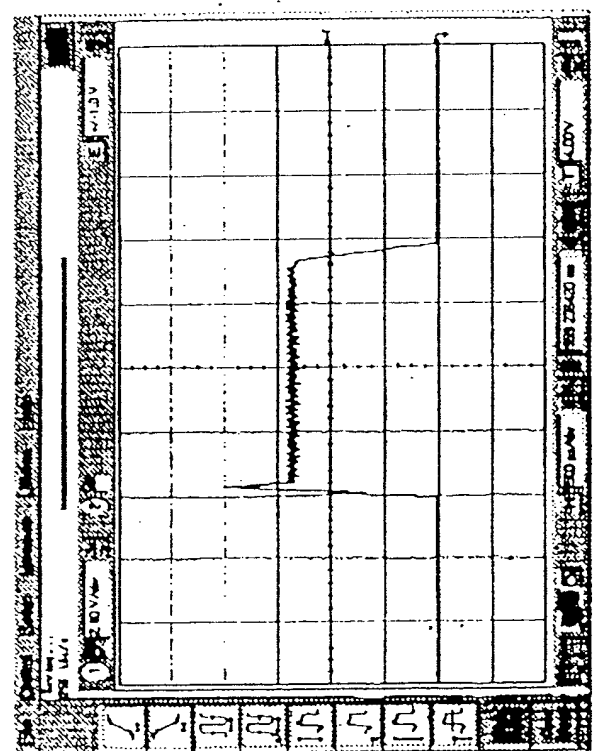
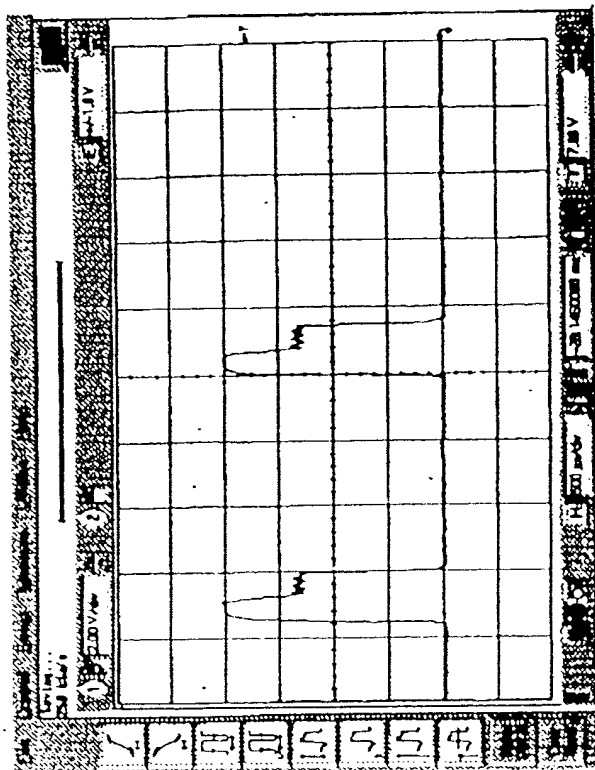
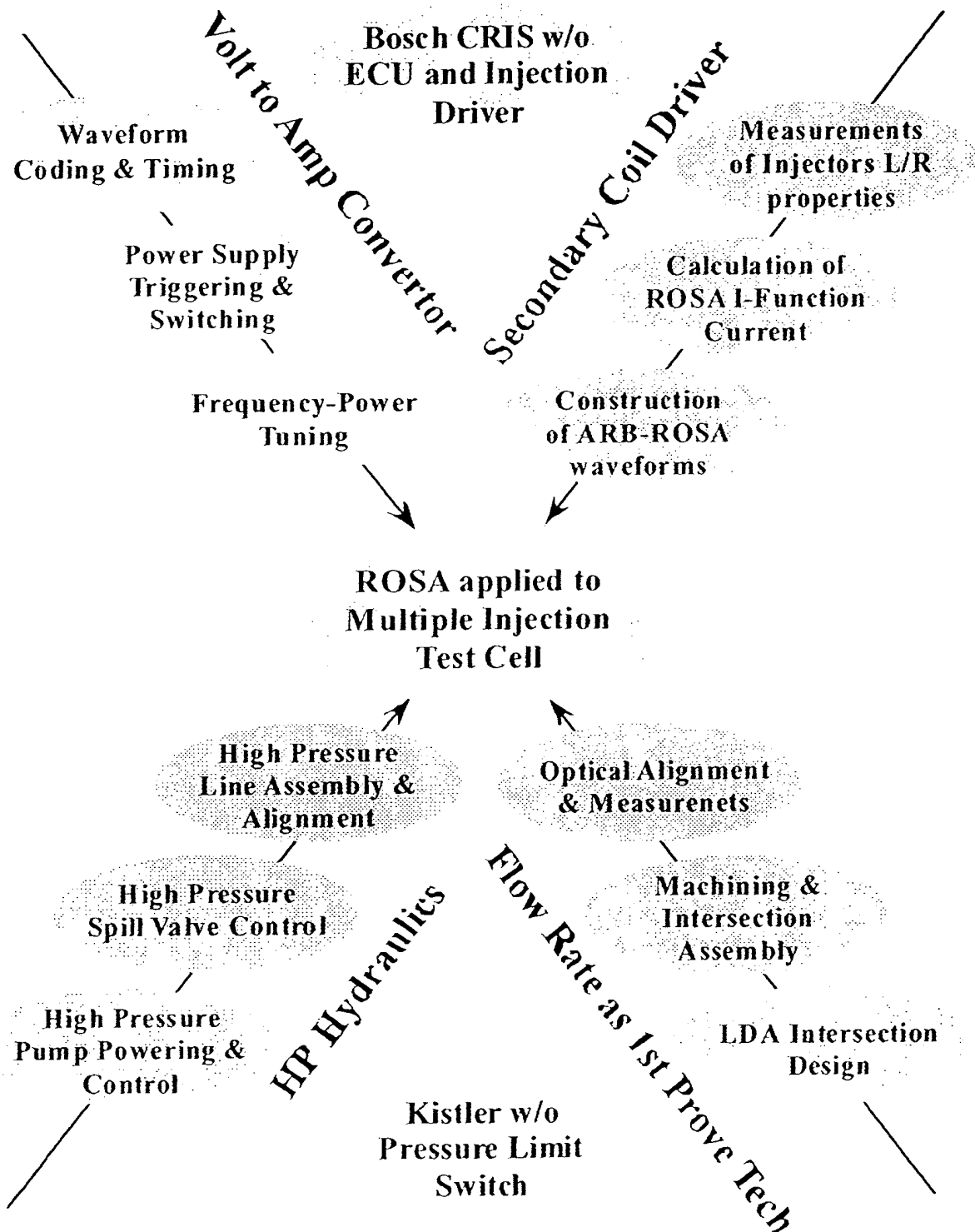


Figure 25

Figure 26

Controllable Multiple Injection System applied to Bosch Common Rail: Solution



Measurement Setup to Verify High Pressure Multiple Injection

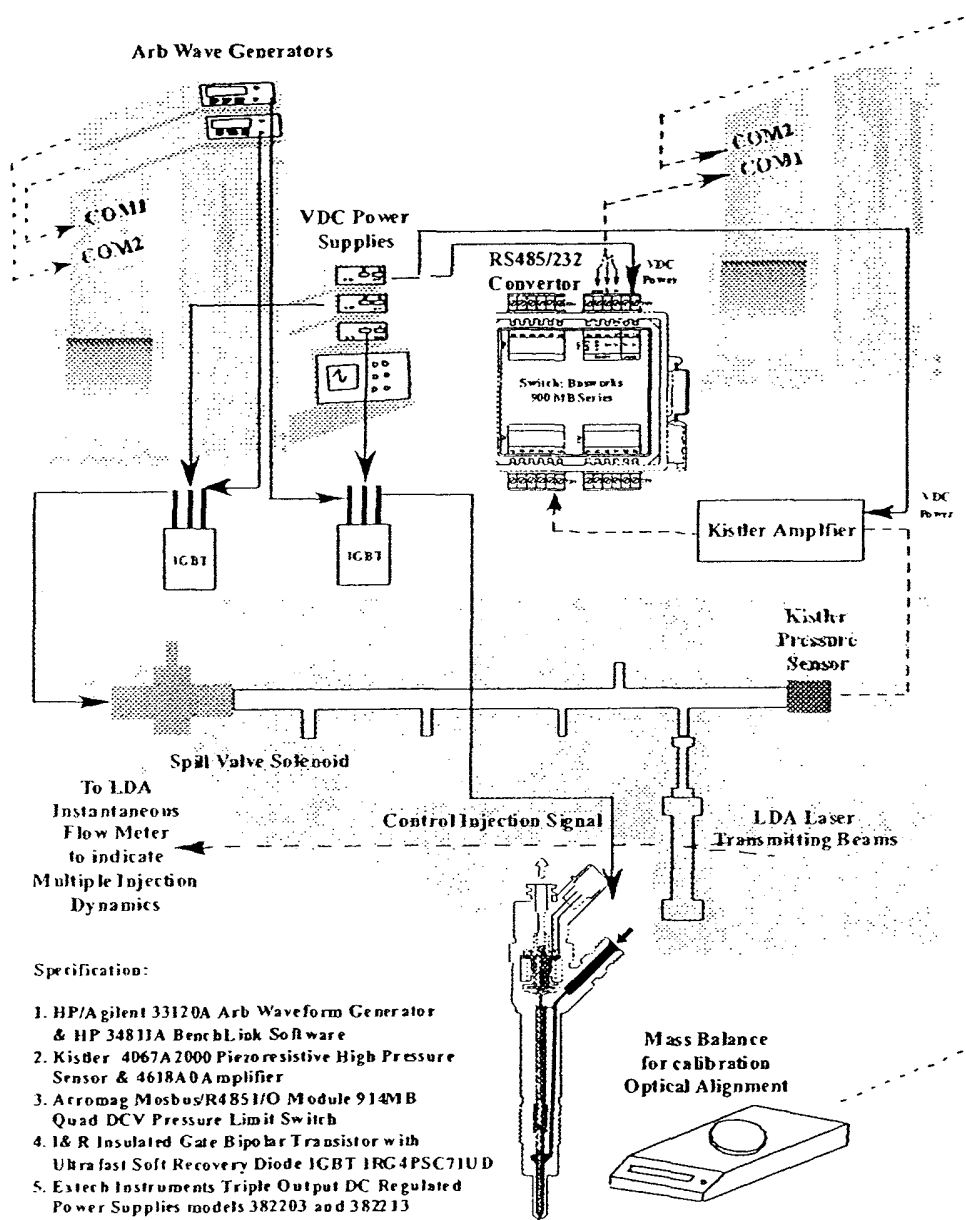
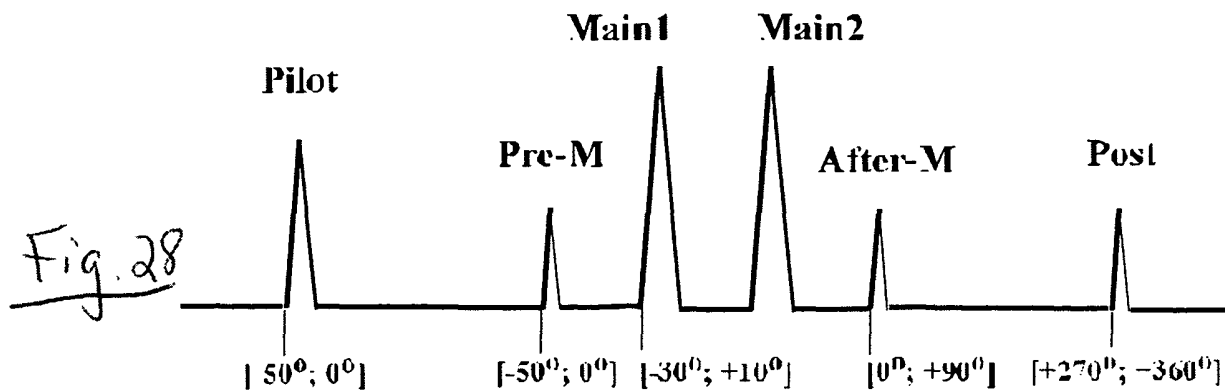
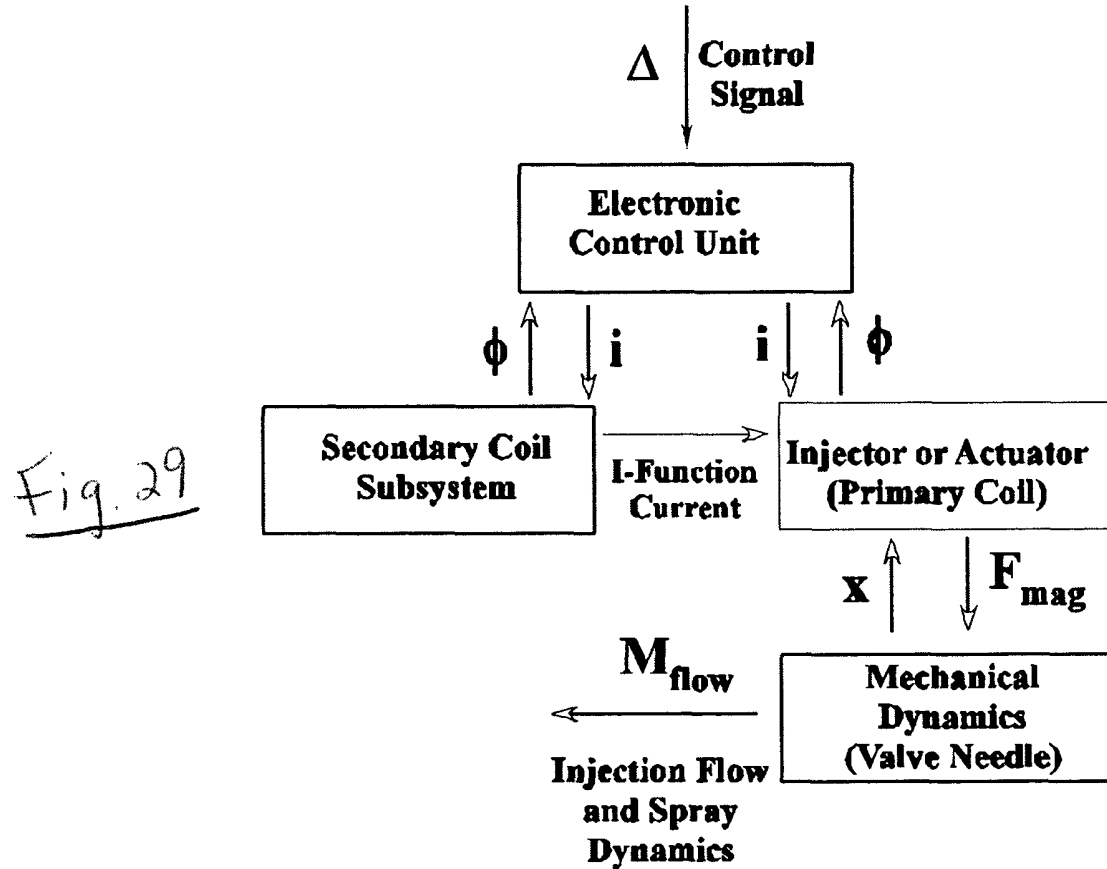


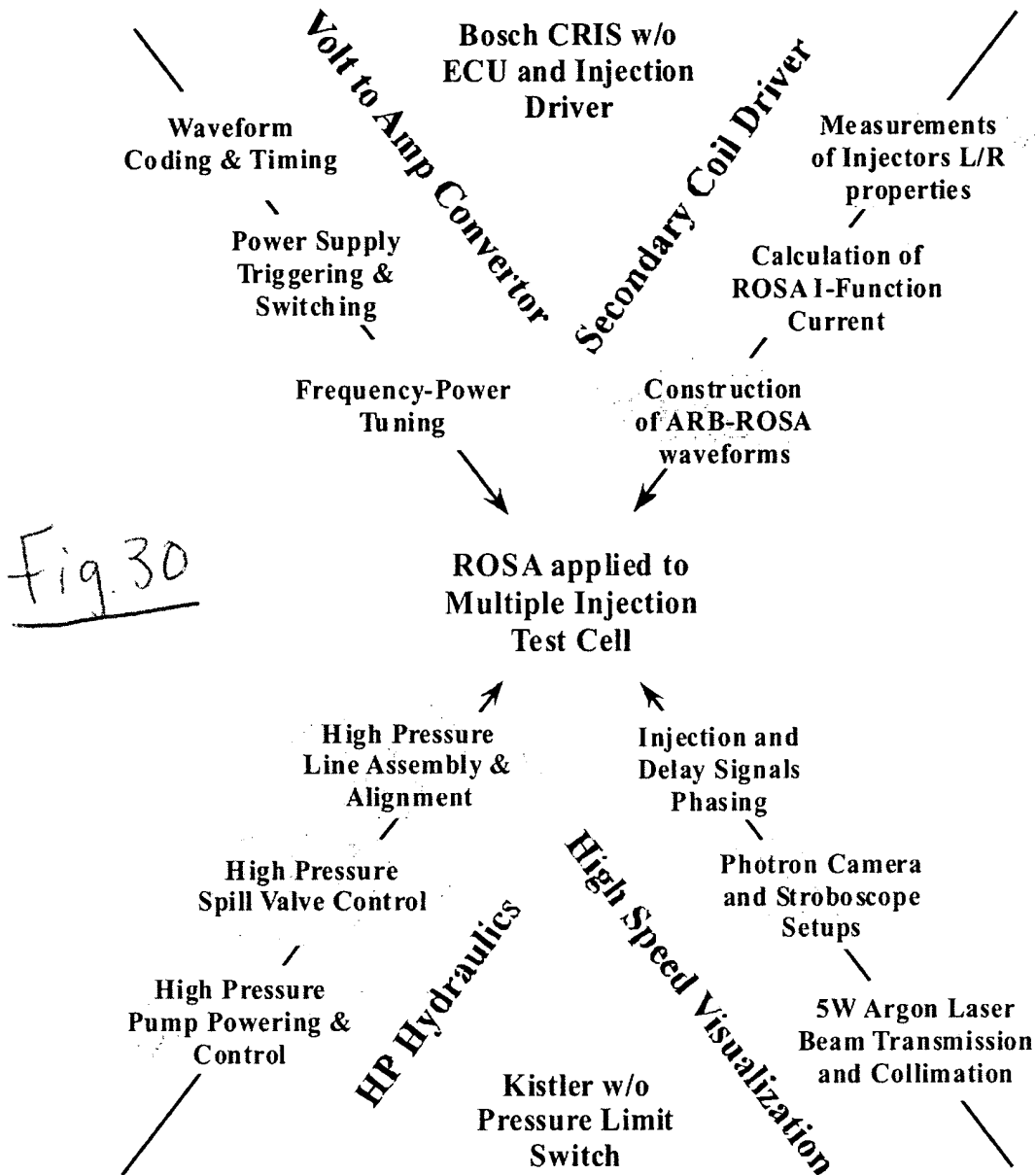
Figure 27



Sketch to six-shot injection cycle along arbitrary referenced camshaft phases.

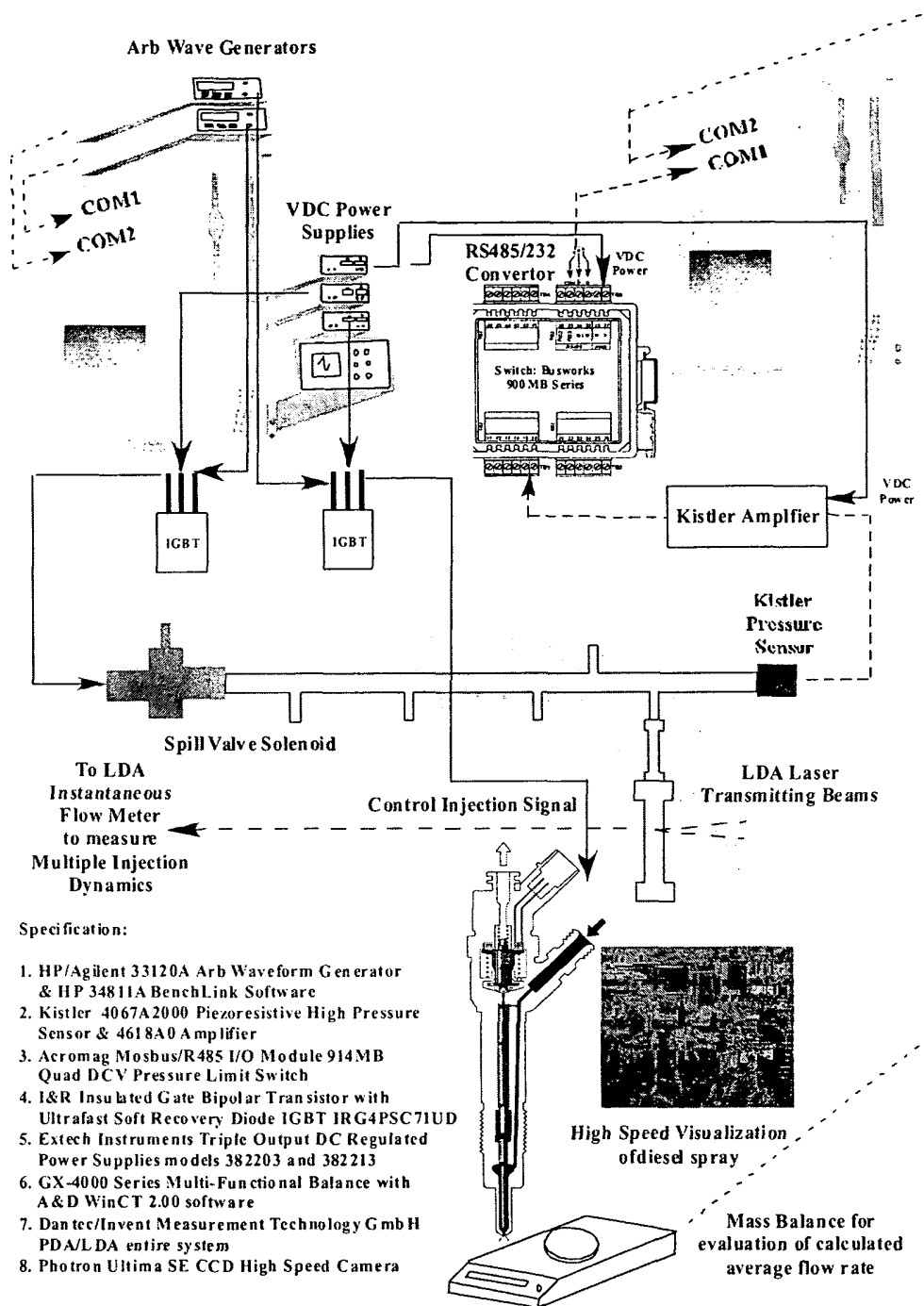


Injection control test configuration used for verification of dynamic response: instantaneous flow rate upstream of injector and spray downstream of injector.



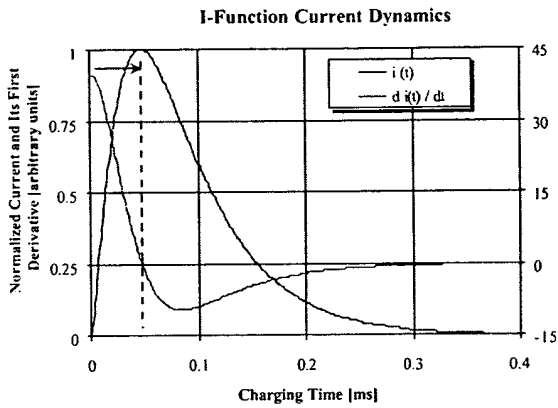
Initial available units of CRIS (grays) and algorithm for construction of ROSA multiple injection control systems.

Fig. 31



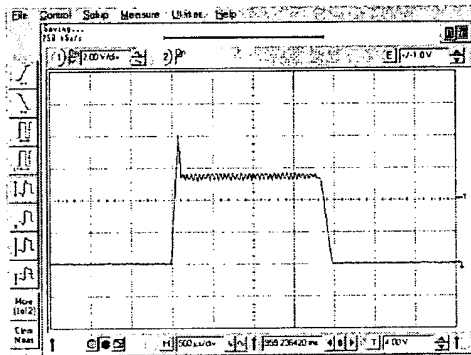
Integrated ROSA measurement configuration to visualize diesel spray by means of high-speed digital camera and quantify injection by means of instantaneous flow rate.

Fig. 32



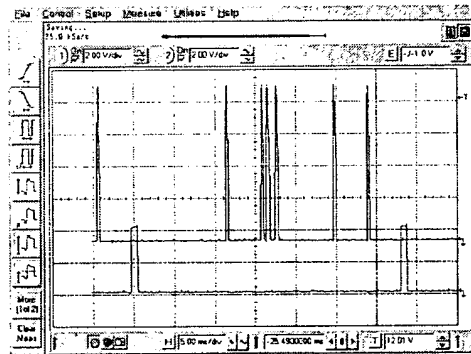
Arbitrary I-Function and its derivative.

Fig. 33



Arbitrary 2 ms Bosch injection.

Fig. 34



Arbitrary 6-shot injection and stroboscope (2nd channel) signals.

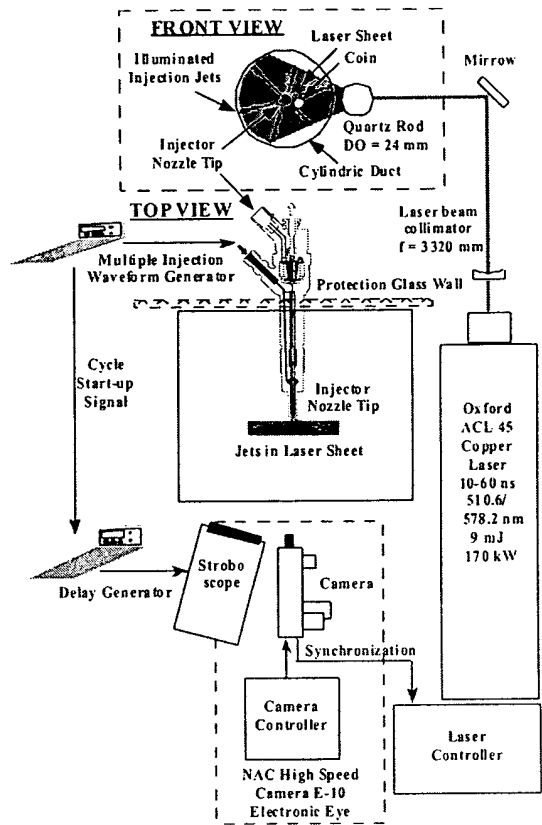
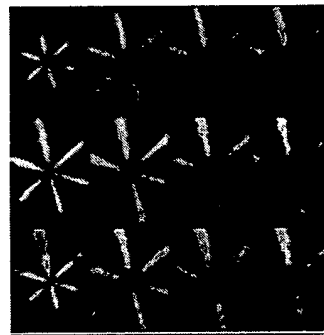


Fig. 35

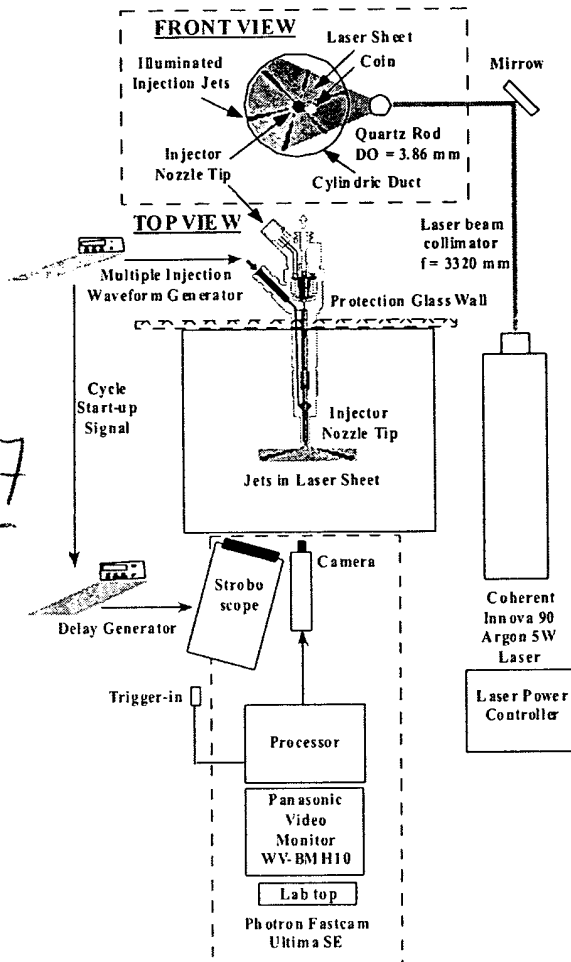
Visualization at 5,000 fps.



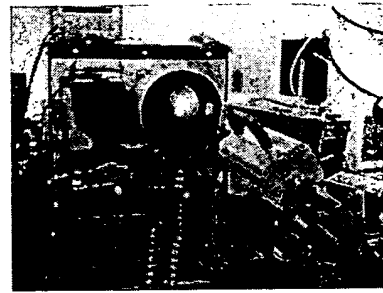
Example of spray at low camera speed.

Fig. 36

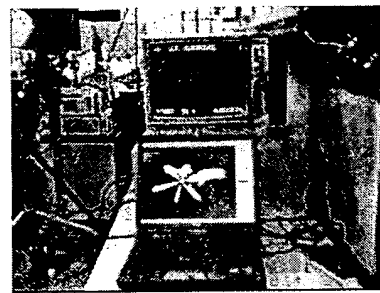
Fig. 37



Visualization speeds of 9,000; 18,000; 27,000 and 40,500 fps



A. Injector setup with strobe scope



B. Signal processor with monitor

Visualization optics setup, white disc is US quarter,

Fig. 39



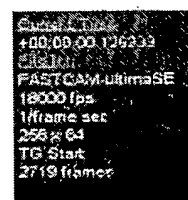
$t = 0.126166 \text{ s}$

$t = 0.126222 \text{ s}$

$t = 0.126277 \text{ s}$

$t = 0.126333 \text{ s}$

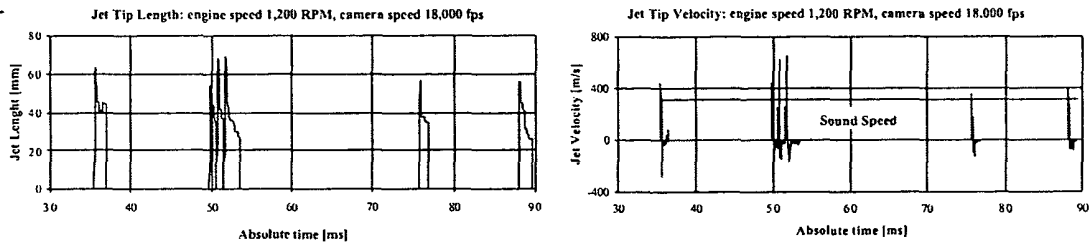
$t = 0.126388 \text{ s}$



$t = 0.126333 \text{ s}$

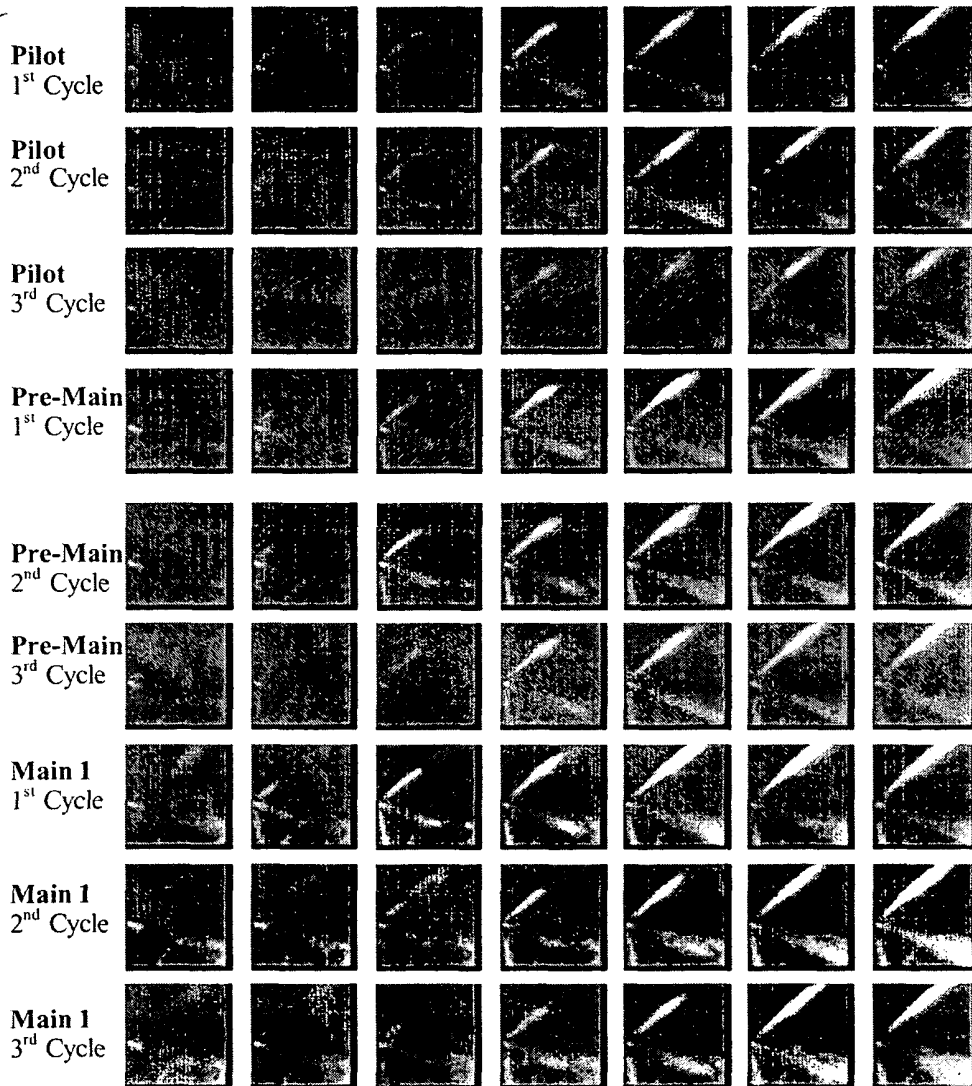
Pilot shot in six-shot injection: engine speed 2,400 RPM, frame duration 55.56 μs , coin size 24.76 mm.

Fig. 40



Liquid jet length and tip velocity for six-shot injection 100 ms cycle:
at engine speed of 1,200 RPM and camera speed of 18,000 fps

Fig. 41



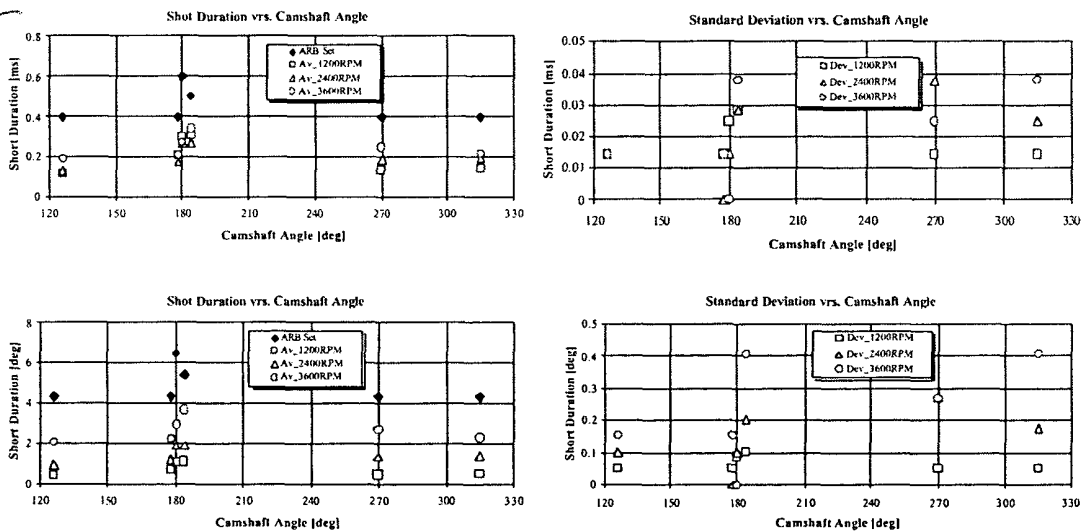
Cycle-to-cycle variability at resolution 24.69 μ s/frame for 6-shot injection, only 4 shots
are shown: engine speed 3,600 RMP, dwell between Pre-Main and Main 1 setup to 200 μ s.

Fig. 42

Waveform Electronic Setup, Engine Speed 3,600 RPM								High Speed Camera Record at Speed of 40,500 fps							
DURATION				PHASES				DURATION				PHASES			
	pts	ms	deg		pts	ms	deg		frames	ms	deg		frame	ms	deg
period	16000	33.3	360	period	16000	33.33	360	period	1350	33.333	360	period	1350	33.333	360
3 Main	288	0.6	6.5		8000	16.667	180.0		11	0.272	2.9		1969	17.210	185.9
dwel1_1	96	0.2	2.2						21	0.518	5.6				
2 Pre_M	192	0.4	4.3		7712	16.067	173.5		8	0.198	2.1		1940	16.494	178.1
1 Pilot	192	0.4	4.3		5600	11.667	126.0		8	0.198	2.1		1762	12.099	130.7
dwel1_2	240	0.5	5.4						28	0.691	7.5				
4 Main_2	240	0.5	5.4		8528	17.767	191.9		14	0.346	3.7		2008	18.173	196.3
5 After_M	192	0.4	4.3		12000	25.000	270.0		9	0.222	2.4		2302	25.432	274.7
6 Post	192	0.4	4.3		14000	29.167	315.0		7	0.173	1.9		2472	29.630	320.0
Pilot-to-Pre_M				1920	4.000	43.2		Pilot-to-Pre_M				170	4.198	45	
Pre_M-to-Main1				96	0.200	2.16		Pre_M-to-Main1				21	0.519	6	
Main1-to-Main2				240	0.500	5		Main1-to-Main2				28	0.691	7	
Main2-to-AfterM				3232	6.733	73		Main2-to-AfterM				280	6.914	75	
AfterM-to-Post				1808	3.767	41		AfterM-to-Post				161	3.975	43	

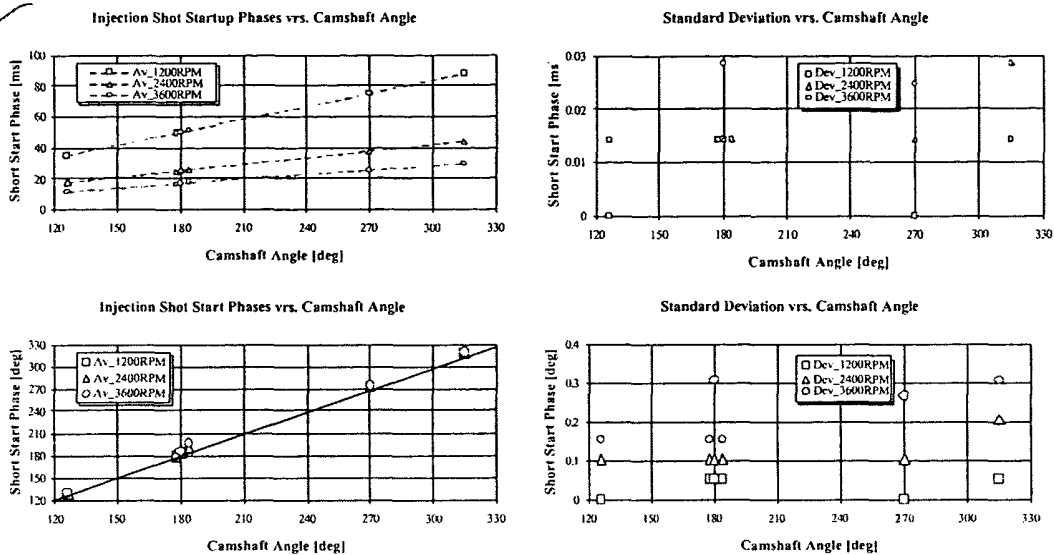
Comparison of dynamic injection timing (on the right) vs. waveform setups of timing (on the left): [pts] - points in ARB waveform generator, [ms] absolute time, [deg] - cam phasing, [frame] number of frames, 1 frame = 24.69 μ s

Fig. 43



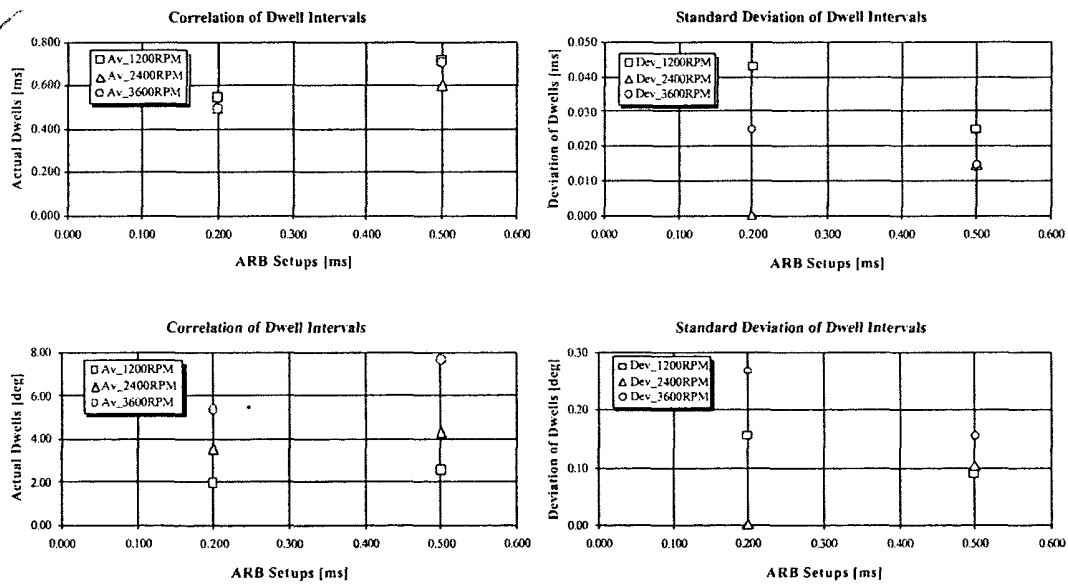
Pilot, Pre-Main, Main1, Main2, After-M, Post shots' duration and its standard deviation in absolute time (2 top plots) and in camshaft angle (2 bottom plots).

Fig. 44

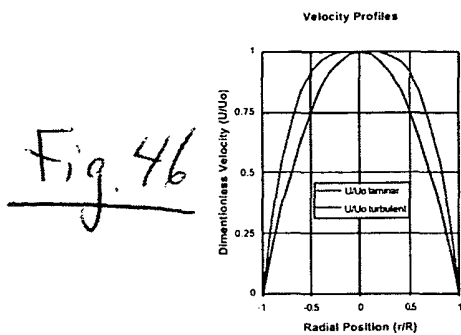


Pilot, Pre-Main, Main1, Main2, After-M, Post shots' startup phase and its standard deviation in absolute time (2 top plots) and in camshaft angle (2 bottom plots).

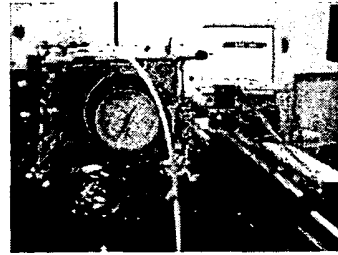
Fig. 45



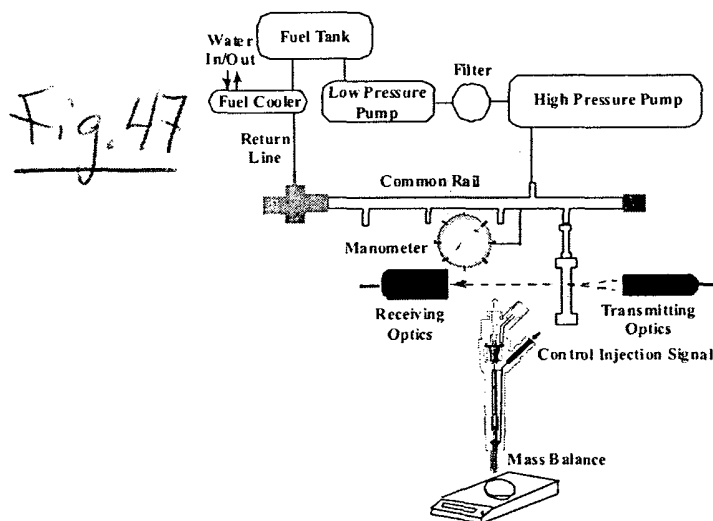
Dwell intervals between Pre-Main and Main1 (dwell 1), Main1 and Main2 (dwell 2) and their standard deviation in absolute time (2 top plots) and in camshaft angle (2 bottom plots).



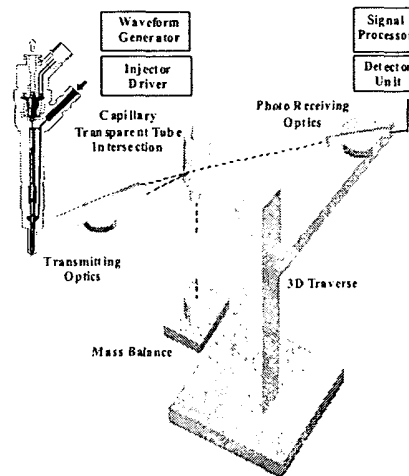
Velocity profiles for fully developed laminar and turbulent pipe flows.



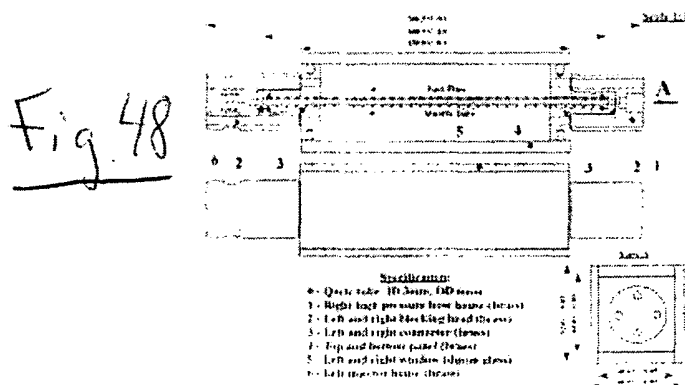
LDA MI-2 cell withstanding
high-pressures up to 2000 bar.



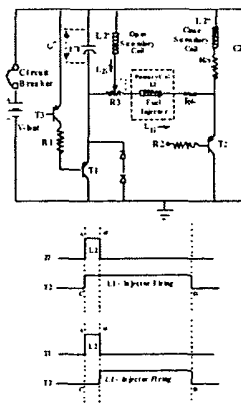
Sketch to high-pressure fuel flow rig and LDA flow rate measurements.



LDA flow rate and mass balance.

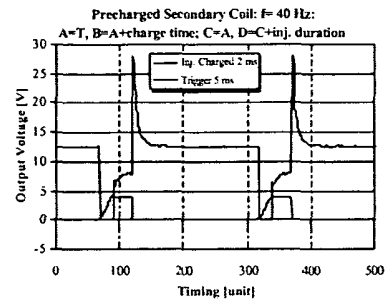
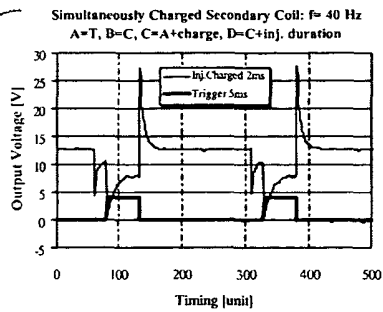


LDA MI-1 cell for injection pressures up to 140 bar



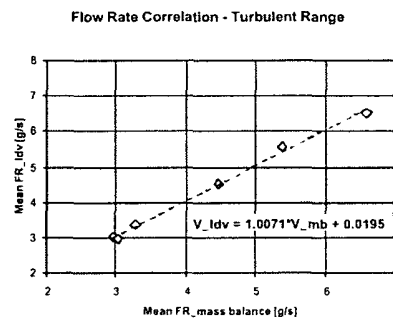
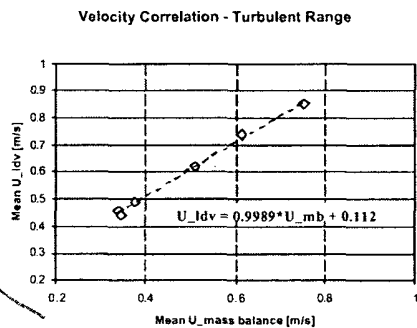
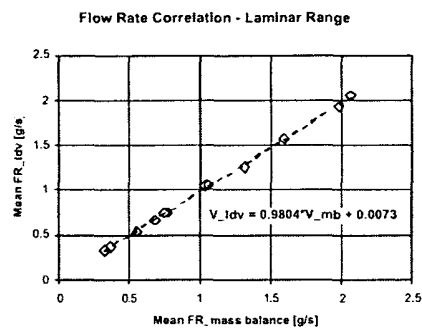
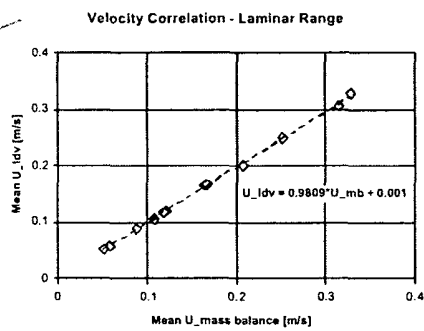
ROSA electronic circuit.

Fig. 52



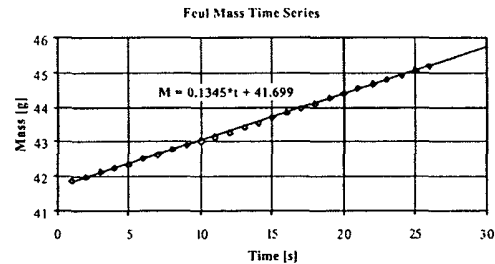
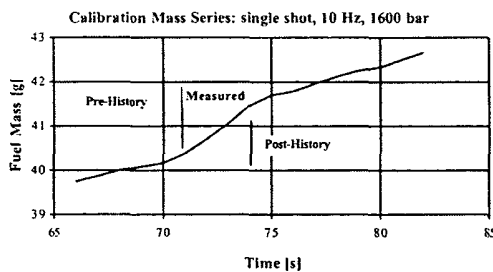
Simultaneous- and pre- charge; bold - injection duration (T2), thin - output from injector.

Fig. 53



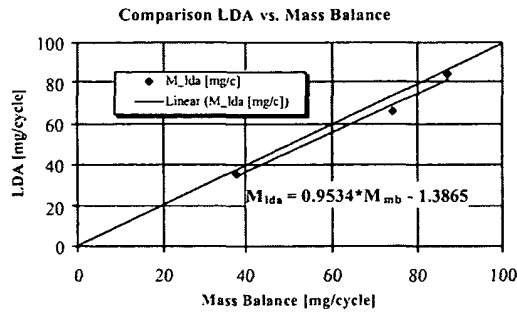
LDA calibration using mass balance measurements.

Fig. 54



ROSA-CRIS diesel injection: mass balance trace including “pre-history”, “measured” and “post-history” injection parts.

Fig. 55



ROSA-CRIS diesel injection:
fuel mass injected per cycle.

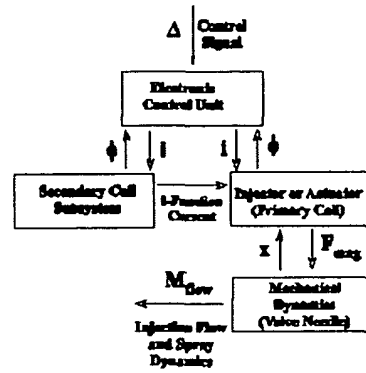
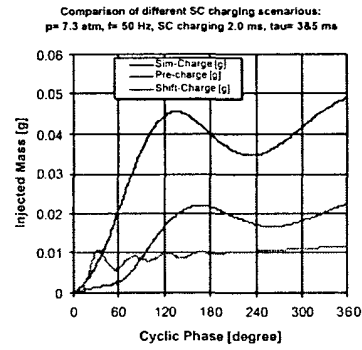
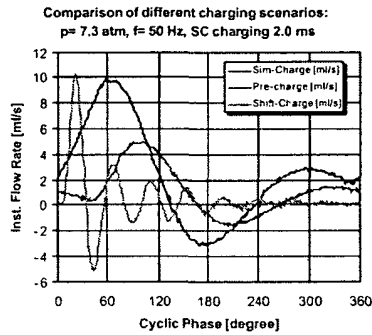


Fig. 56

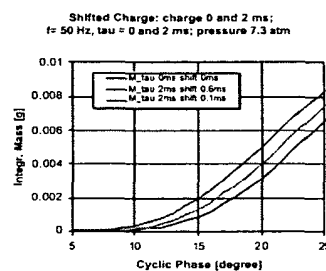
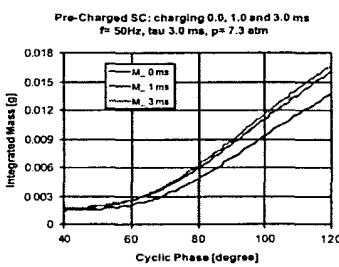
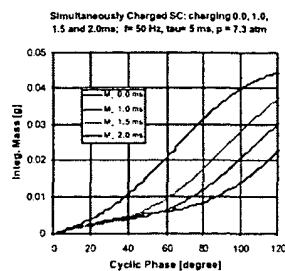
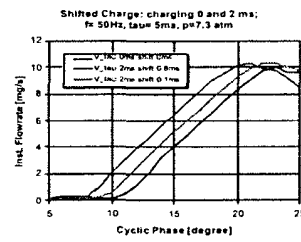
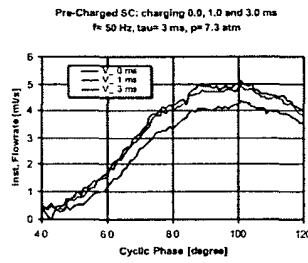
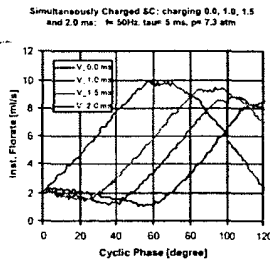
Test configuration for
verification of injection dynamics.

Fig. 57



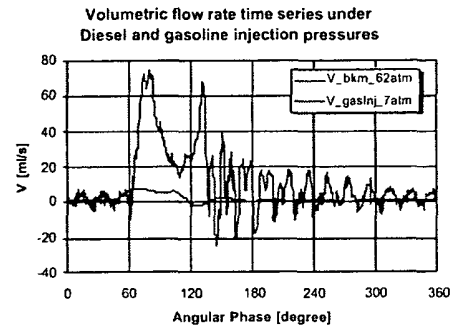
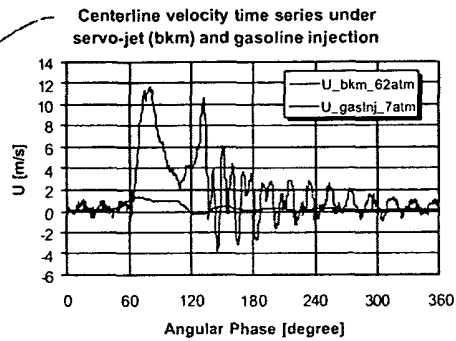
Comparison of different SC charging scenarios at the same injection condition:
instantaneous volumetric flow rate and integrated injection mass.

Fig. 58



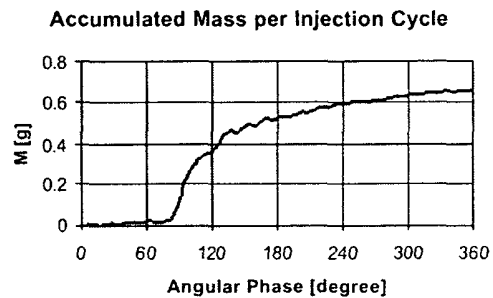
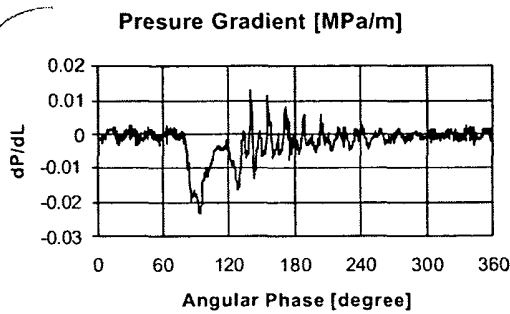
Flow rate (top row) and integrated mass (bottom row) obtained for:
simultaneous charge – 1st column, pre-charge – 2nd column, tuned charge – 3rd column

Fig. 59



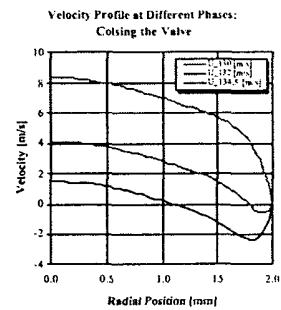
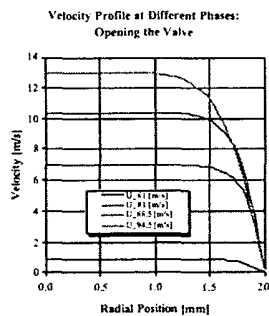
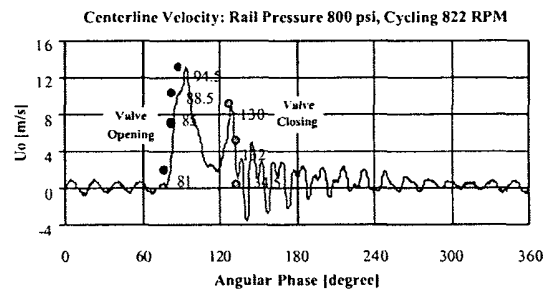
Velocity and flow rate: injection pressures - 62 (servo-jet) and 7 bar (gasoline).

Fig. 60



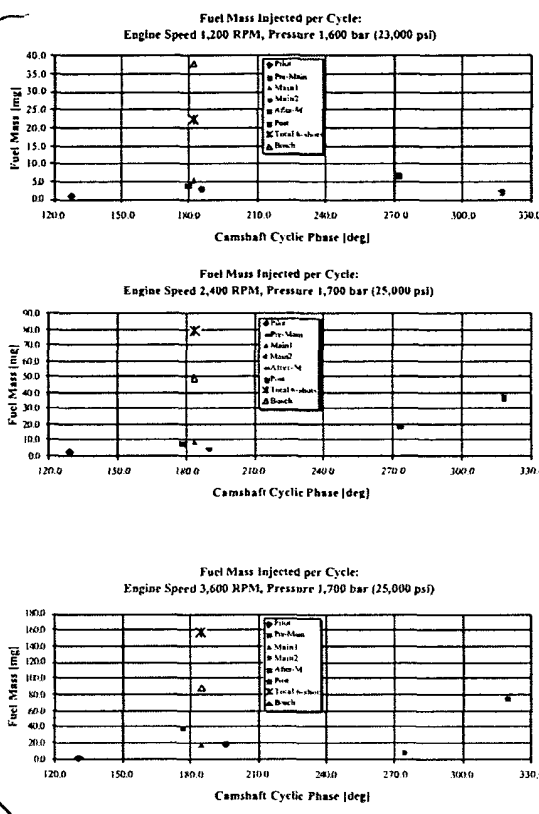
Pressure gradient and accumulated mass: $p = 62$ bar, $f = 11$ Hz, duration 15 ms.

Fig. 61



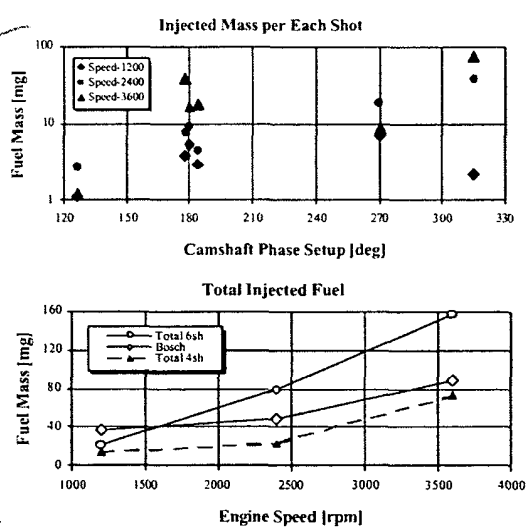
Velocity time series with selected angular phases (top) and velocity profiles for two stages: opening (bottom left) and closing (bottom right) of injector valve.

Fig. 62



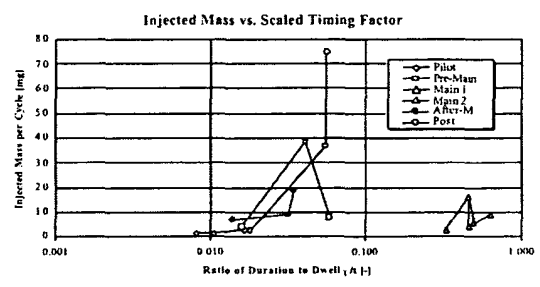
Fuel masses for 6-shot injection and Bosch 1 ms single shot injection.

Fig. 63



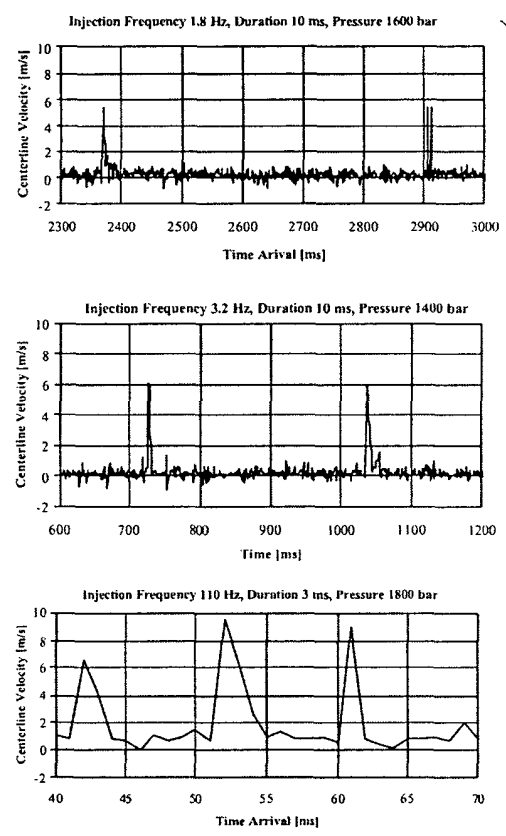
Summary to dynamic of 6-shot injection and integrated fuel mass.

Fig. 64



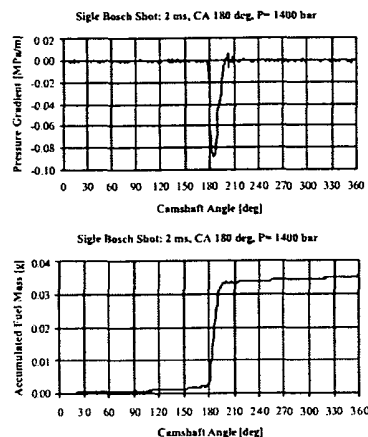
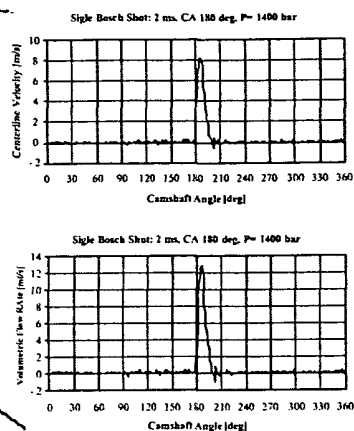
Separation of low and high frequency domains by scaling timing factor τ/t

Fig. 64



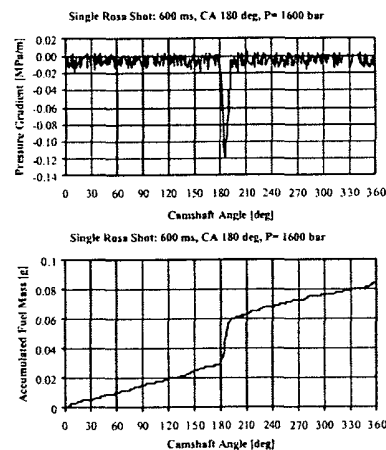
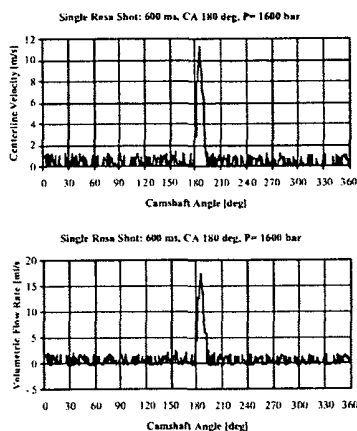
Examples of LDA time arrival series.
data rates: top – 2.964 , mid – 2.641,
bottom – 0.051 kHz.

Fig. 66



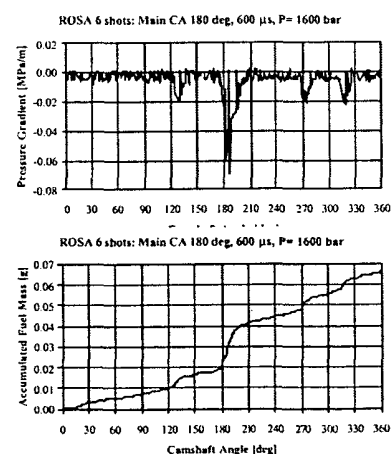
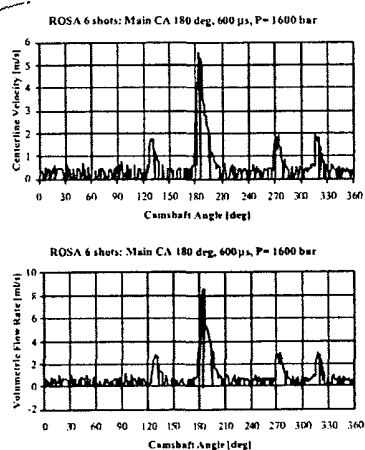
2-ms single reference injection: SOI at 180°, p= 1400 bar.

Fig. 67

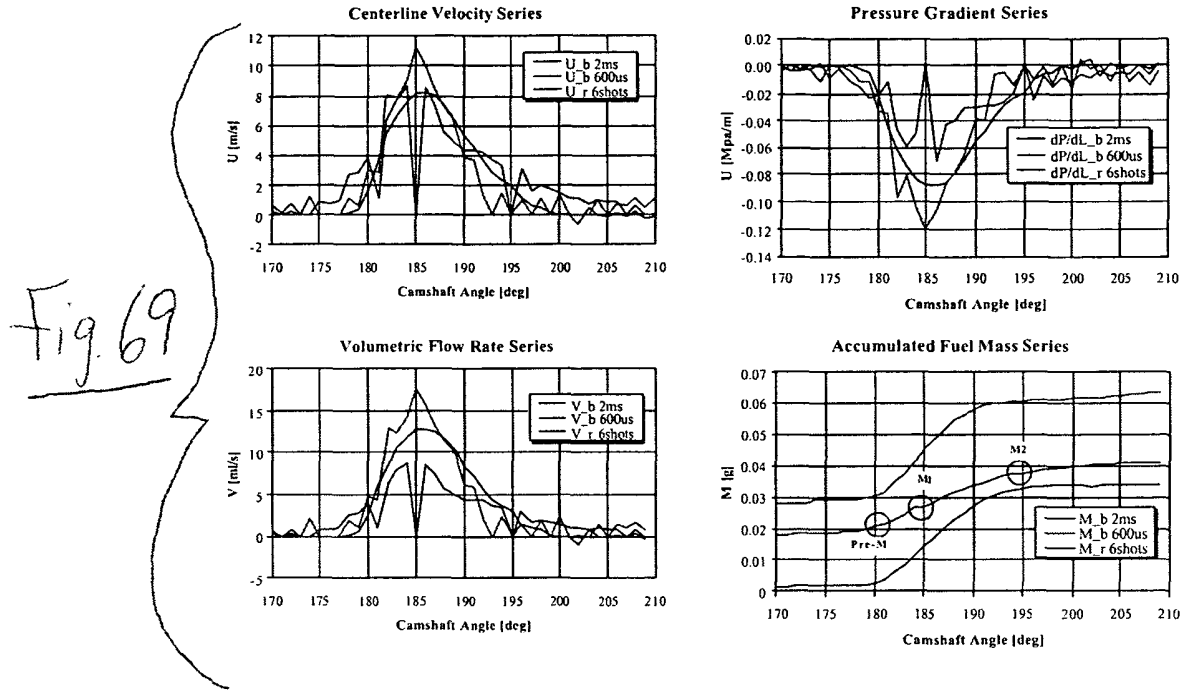


ROSA-controlled single shot injection: SOI at 180°, p= 1600 bar.

Fig. 68



ROSA-controlled six shots injection: Main1 SOI at 180°, p= 1600 bar.



Comparison of dynamics for 2-ms reference single injection, $p=1400$ bar and ROSA-controlled six shots injection, $p=1600$ bar.

Fig. 70

	shot/pass	Start deg	End deg	duration ms	masses mg	% of total %
1	deliver 1	0	125	34.72	10.74	14.8
2	Pilot	125	133	2.22	4.18	5.8
3	deliver 2	133	175	11.67	4.33	6.0
4	Pre-Main	175	182	1.94	4.47	6.2
5	Main 1	182	186	1.11	7.30	10.1
6	Main 2	186	196	2.78	11.65	16.1
7	deliver 3	196	269	20.28	10.62	14.7
8	After-M	269	281	3.33	5.81	8.0
9	deliver 4	281	315	9.44	5.02	6.9
10	Post	315	327	3.33	4.76	6.6
11	deliver 5	327	360	9.17	3.54	4.9
	Total:				72.42	100.0
	injected				38.17	52.7
	deliver				34.25	47.3

Integrated Masses per Active and Passive (deliver) Injection Events.